WL-TR-97-4017

The Evaluation of Thermally Induced Damage in Polymer Matrix Composites via a Design of Experiments Approach

Mark D. Kistner
Systems Support Division
Materials Behavior and Evaluation Section

Ronald J. Kuhbander
University of Dayton Research Institute

Daniel B. McCray
Southwest Ohio Council for Higher Education

January 1997

FINAL REPORT FOR: 07/01/92 - 07/01/96

Approved for public release; distribution unlimited

MATERIALS DIRECTORATE
WRIGHT LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7734

NOTICE

WHEN GOVERNMENT DRAWINGS, SPECIFICATIONS, OR OTHER DATA ARE USED FOR ANY PURPOSE OTHER THAN IN CONNECTION WITH A DEFINITELY GOVERNMENT-RELATED PROCUREMENT, THE UNITED STATES GOVERNMENT INCURS NO RESPONSIBILITY OR ANY OBLIGATION WHATSOEVER. THE FACT THAT THE GOVERNMENT MAY HAVE FORMULATED OR IN ANY WAY SUPPLIED THE SAID DRAWINGS, SPECIFICATION, OR OTHER DATA, IS NOT TO BE REGARDED BY IMPLICATION, OR OTHERWISE IN ANY MANNER CONSTRUED, AS LICENSING THE HOLDER OR ANY OTHER PERSON OR CORPORATION; OR AS CONVEYING ANY RIGHTS OR PERMISSION TO MANUFACTURE, USE, OR SELL ANY PATENTED INVENTION THAT MAY IN ANY WAY BE RELATED THERETO.

THIS REPORT HAS BEEN REVIEWED BY THE OFFICE OF PUBLIC AFFAIRS (ASC/PA) AND IS RELEASABLE TO THE NATIONAL TECHNICAL INFORMATION SERVICE (NTIS). AT NTIS, IT WILL BE AVAILABLE TO THE GENERAL PUBLIC, INCLUDING FOREIGN NATIONALS.

THIS TECHNICAL REPORT HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION.

Mark D. Kistner

MARK D. KISTNER, MATLS ENGINEER
ENGINEERING AND DESIGN DATA TEAM
ACQUISITION SYSTEMS SUPPORT BRANCH
SYSTEMS SUPPORT DIVISION

James L. Folck

JAMES L. FOLCK, ACTING CHIEF
MATERIALS ENGINEERING BRANCH
SYSTEMS SUPPORT DIVISION

Gary K. Waggoner

GARY K. WAGGONER
CHIEF
SYSTEMS SUPPORT DIVISION

IF YOUR ADDRESS HAS CHANGED, IF YOU WISH TO BE REMOVED FROM OUR MAILING LIST, OR IF THE ADDRESSEE IS NO LONGER EMPLOYED BY YOUR ORGANIZATION, PLEASE NOTIFY WL/MLSC, 2179 TWELFTH STREET, SUITE 1, WRIGHT-PATTERSON AFB OH 45433-7718 TO HELP MAINTAIN A CURRENT MAILING LIST.

COPIES OF THIS REPORT SHOULD NOT BE RETURNED UNLESS RETURN IS REQUIRED BY SECURITY CONSIDERATIONS, CONTRACTUAL OBLIGATIONS, OR NOTICE ON A SPECIFIC DOCUMENT.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	Jan 1997	Final: 07/92 to 07/96

4. TITLE AND SUBTITLE
The Evaluation of Thermally Induced Damage in Polymeric Matrix Composites via a Design of Experiments Approach

5. FUNDING NUMBERS
CF 33615-95-D-5616
PE 62102F
PR 4349
TA S2
WU 00

6. AUTHOR(S)
Mark D. Kistner, Ronald J. Kuhbander, and Daniel B. McCray

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Dayton Research Institute
300 College Park Avenue
Dayton Oh 45469-0130

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Materials Directorate
Wright Laboratory
Air Force Materiel Command
Wright-Patterson AFB OH 45433-7734
POC: Mark Kistner, WL/MLSC, 937-255-5128

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
WL-TR-97-4017

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
As of the date of this report overheat damage is an area of concern for the supportability of polymeric matrix composites, since a significant amount of strength is lost, up to 30% in shear, before this a damage is detectable by standard ultrasonic inspections techniques. This report takes the approach of using a design of experiments to determine which factors and interactions significantly affect the heat damage behavior of polymeric matrix composites. A 64-run design was developed which could rank all the identified factors and interaction. A quartz lamp bank is used to provide one-sided radiant heating. Mechanical testing includes four-point shear, and 24:1 four point flexure. The factors were analyzed and ranked for both test methods. Also, the data was entered two different ways (1) as five replicates of the same exposure conditions, and (2) as average values. The data entered as replicates showed many more of the factors and interactions to be significant than when the data was entered as averages. The work has identified the significant factors and two-level interactions affecting the heat damage behavior of polymeric matrix composites. Follow-on efforts should be orientated at identification of heat damage failure mechanisms and nondestructive methods to detect these identified mechanisms.

14. SUBJECT TERMS
Design of Experiments, Heat Damage, Polymeric Matrix Composite, Thermally Inducted Damage, AS4/3501-6, AS4/977-3

15. NUMBER OF PAGES
52

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

The authors wish to thank Mr. Mark Forte for obtaining funding for this effort. This effort was conducted as an in-house research effort under an on-site contract F33615-89-C-5643 and F33615-95-D-5616 with the University of Dayton Research Institute (UDRI). Mr. Nicholas Olson of UDRI instrumented and exposed panels via a computer controlled radiant quartz lamp bank.

The authors contributions also deserve some explanation. Mr. Mark Kistner with the help of an Adhoc Committee decided on which factors and interactions of those factors to try to evaluate and developed an experimental design to rank their significance. Mr. Ron Kuhbander developed a scheme to track the panels to assure that they were properly manufactured, exposed, and tested. Mr. Daniel McCray did much of the hands-on work of laying up the panels in the proper orientation and performing the mechanical testing.

1.0 INTRODUCTION

This work is being performed out of the Systems Support Division of Wright Laboratory at Wright-Patterson Air Force Base. The concern of this group is that we have adequate capability to repair composite structure on Air Force weapon systems. For heat damaged structure the standard ultrasonic C-scan only detects heat damage after a delamination has occurred. A problem with heat damaged structure is that up to a 30% decrease in interlaminar shear strength occurs before a delamination is produced. The Systems Support Division would like to be able to detect this degraded strength for nondelaminated structure. This capability would ideally allow the determination of which portion of an heat damaged structure has suffered a strength reduction and needs to be repaired. During the repair process damaged material is removed via sanding or scarfing. Also, the repair equipment and inspection equipment need to be easily portable, since this equipment is transported to the location of the plane. Thus, for the nondestructive method to be most useful, it must be able to easily detect the heat damage zone through the thickness and be easily portable. Electrical power for inspection equipment is typically provided by 110V house power or 110V power provided by a portable generator, so this equipment needs to require no special power requirements. While it is valuable to know the ultimate goal for this research, the scope of this report is to use a design of experiments approach to gain a basic understanding of which factors and two level interactions of factors influence the heat damage of PMCs. Follow-on work to this report is to identify which failure modes cause strength degradation via heat damage for graphite/epoxy and the evaluation or development of nondestructive inspection/ evaluation (NDE/NDI) techniques to detect these failure modes.

This report will include the development of an experimental design, evaluation of the experimental data, and ranking of significant factors and two level interactions. For the decision on which factors and two level interactions to include in this study, an ADHOC Committee was formed. This committee using their experience was able to limit this study to 9 main factors and 19 two level interactions. In order to test all conditions separately for a 9 factor experiment (without replication) would require 2^9 or 512 tests. To evaluate the 28 factors or interactions selected required an experimental design with a minimum of 32 tests, but this design resulted in too much confounding. Confounding is where the effect of two or more interactions or factors are not mathematically separable due to their residing in the same column. To eliminate this confounding a 64-run design was utilized. Thus, by using a Taguchi type of partial factorial design the selected factors and two level interactions were able to be evaluated in 64/512 or 1/8 the number of runs.

2.0 BACKGROUND

Historically, graphite/epoxy composites have suffered heat damage from various sources such as fires, mishaps during ordinance firing, or excessive exhaust gas impingement and the such. This type of heat damage is above that which the structure is designed to tolerate. The current problem with heat damage is that damage can only be detected by standard nondestructive inspection techniques, such as ultrasonic C-scan, after delaminations have occurred. Significant degradation in mechanical properties of 30% or more for shear strength may occur before delamination. For the systems support branch to adequately evaluate and repair heat damaged structures require the ability to go to an aircraft, examine the structure for heat damage (including moderately heat damaged structure), and the ability to remove the damage and repair the structure. Currently, methods to remove and repair the structure, such as bolted or scarfed repair, have been developed, but the NDI techniques to adequately evaluate the structure are lacking in the moderately heat damaged region. To develop a NDI technique requires an understanding of the mechanisms of heat damage in graphite/epoxy composites. This effort is to gain a better understanding of these mechanisms.

An ADHOC committee consisting of Air Force, Navy, Army, University of Dayton Research Institute (UDRI), and Oak Ridge National Laboratory personnel was formed. This group's knowledge of heat damage of composites helped to select reasonable levels of factors and decide on which factors and interactions were to be evaluated in a design of experiments approach. A design of experiments approach was selected, since this approach could significantly reduce the amount of testing, and allowed a method to evaluate the significance of each factor or each two-level interaction.

Prior work at the UDRI showed that for one-sided heating, using radiant heating via a quartz heat lamps produced controllable and rapid heating (Ref 8). As a result quartz heat lamps were selected for the heating method for this study, though as is discussed in Section 4.1, the lamp bank and control method were significantly modified from Ref. 8. This reference also suggested that on a plot of nominal exposure time versus nominal exposure temperature an "apparent damage threshold" can be drawn. This study measured compression and flexure strength. Compression strength was found to be more degraded than flexure strength for higher temperature exposures and less degraded for lower temperature exposures. Since the current study is interested in examining the onset of degradation, flexural strength appears to be promising for the measure of heat damage degradation.

Street, Russell and Bonsang (Ref 4) examined the degradation in Mode I fracture toughness as a function of time and temperature. They contributed the loss in mechanical properties to deterioration of the epoxy as opposed to fiber or fiber-matrix interfacial weakening. They also measured shear strength, glass transition temperature, and Barcol hardness finding shear strength to be more sensitive to toughness loss than hardness. Their data for glass transition temperature showed an increase for lower temperature exposures above the cure temperature then a decrease as higher temperatures are reached. This presents a problem when trying to determine the exposure conditions for a heat damaged structure, since for the same measured glass transition temperature and time, two potential exposure temperatures are indicated. Which exposure temperature is correct can not be determined by this test alone. Other conclusions for this report are that the measured G_{ic} were found to be more sensitive than G_{IIc} for measuring toughness degradation.

3.0 DESIGN OF EXPERIMENTS APPROACH

The use of a design of experiments requires a high level of knowledge of the subject matter. Since the design is a fractional design, the proper selection of interactions to examine is important. An ADHOC committee on heat damage was formed to decide which factors and two level interaction of factors may be significant. The design tries to separate the identified factors and identified two level interactions into separate columns of the screening design matrix. The design may mix factors or identified two level interactions with interactions which are thought to be insignificant. If it turns out that one or more of the interactions which is thought to be insignificant is significant, this effect will not be separable from the identified factor or interaction and is said to be confounded. The selection of factors, interactions, and levels is discussed in Section 3.1.

Another key to the successful use of an experimental design is that the measure of merit needs to be sensitive to the effect. In this study the effect is the actual decrease in mechanical properties due to heat damage, while the measure of merit is the measured shear or flexure strength determined experimentally. The measure of merit should also have a small level of error compared to the effect being measured. The selection of the measure of merit is further discussed in Section 3.2.

Section 3.3 discusses the development of the screening design test matrix using a Taguchi approach. To aid in the data reduction a software package called Statgraphics Plus For Windows by Manugistics is utilized. The direct outcome of the experimental design is the ability to rank which factors or interaction of factors have the most significant effect on mechanical flexure and shear strength. Also, the program is able to determine the average error. The significant effects will be larger than the average error. The chance that the effect is due to random error becomes greater as the magnitude of the effect approaches the value of the average error. The scope of this report will cover the results of the design of experiments, further work will involve the identification of failure mode and nondestructive methods to detect them.

3.1 SELECTION OF FACTORS AND LEVELS

An Adhoc Committee was formed to select the factors and two level interactions to evaluate under this effort. The committee consisted of Air Force, Navy, University of Dayton Research Institute, and Oak Ridge National Laboratory personnel. To aid in the selection of factors the committee was encouraged to propose as many heat damage related factors and levels as possible. Then the factors and levels were organized into "tree and leaf chart" as is shown in Figure 1. The "tree and leaf chart" is organized such that the trunk is the most generic portion of the diagram and the branches are most specific. These diagrams helped the group to decide which factors need to be addressed and if the factor has multiple subbranches on it, which levels to evaluate. For example, in Figure 1, the branch "reinforcement-fiber", three levels exist; cloth, unidirectional, and discontinuous. The committee decided not to evaluate discontinuous because the applications that the committee was most concerned with use continuous fibers. Thus, two

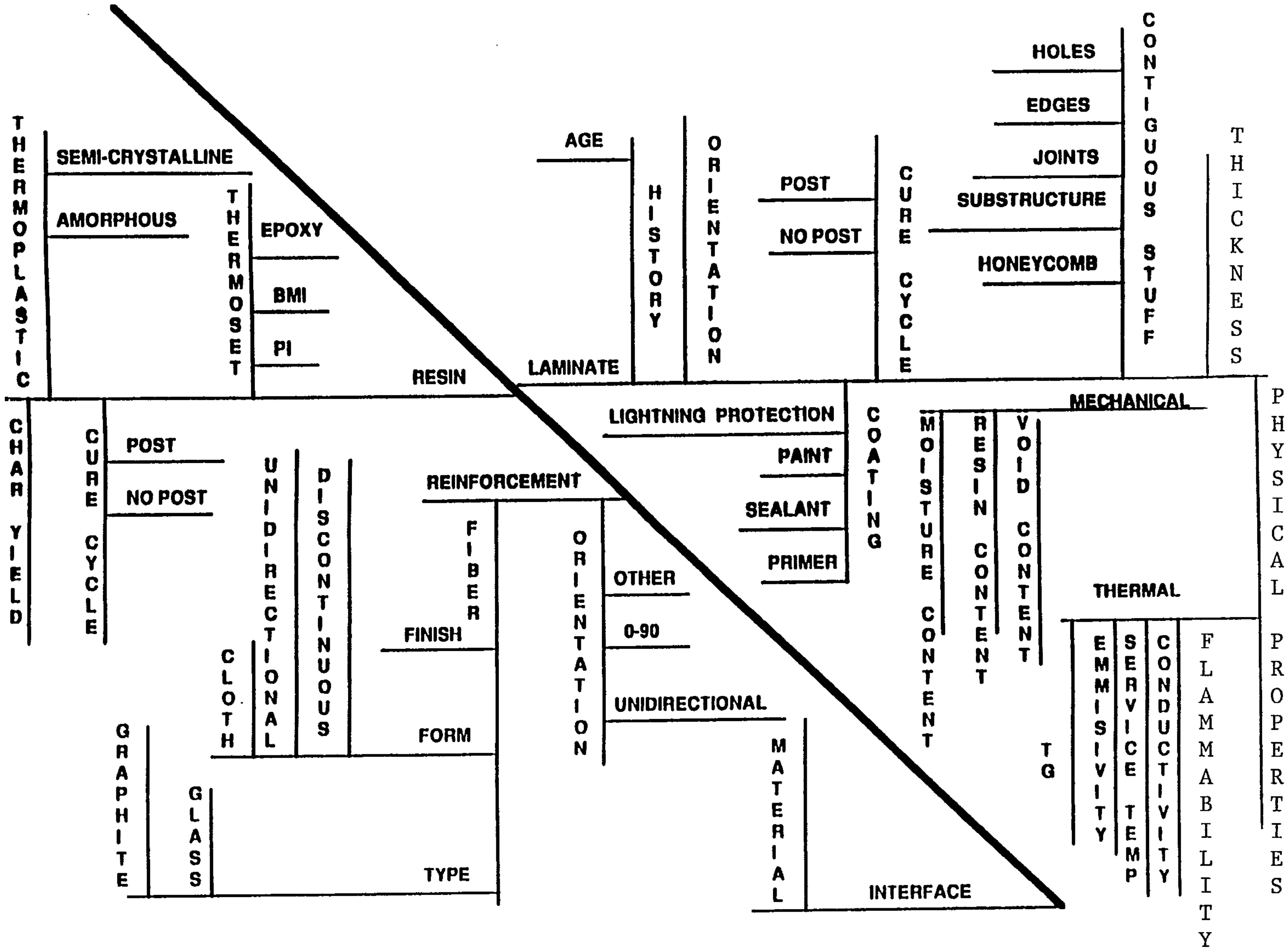


Figure 1. Tree and Leaf Diagram for Materials

levels remained; unidirectional and cloth. After going through this process the remaining factors and levels were further specified, as is shown in Table 1. Some of these factors require further explanation.

For the factor coating, as fabricated and painted was chosen. The paint system used was the same as the light gray color used on the F-16 aircraft. This system consists of an epoxy primer, type 44-GN-24, and a polyurethane paint of type MIL-C-85285B, Type I with a camouflage gray color 36375. Both the primer and paint were manufactured by Deft Inc.

The factor cure cycle is used to simulate the effect of the material being exposed to several cure cycles before being exposure to an over-heat condition. This may occur for repaired structure, since the material is initially cured to manufacture the part, and experiences additional cure cycles when a patch is bonded or cured on to the repair area. The repair cure cycle is ideally at a lower temperature that the original material cure cycle, but for simplicity in this study multiple simulated original cure cycles where utilized. For this study, the high level consists of three cure cycles, and the low level consists of only the original material manufacture cure cycle. The cure cycle for 3501-6 epoxy matrix composites is as follows:

1. Apply full vacuum and 15 psi pressure
2. Heat at 3.4°F per minute to 225°F
3. Apply 85 psi pressure and hold 75 minutes
4. Heat at 2.7°F per minute to 350°F and hold 60 minutes while maintaining 85 psi and full vacuum
5. Cool at 4°F per minute

Additional cure cycles for 3501-6 matrix composites were performed free standing in an oven using the following cycle:

1. Heat to 225°F at 3.5°F per minute
2. Hold at 225°F for 75 minutes
3. Heat to 350°F at 2.5°F per minute
4. Hold at 350°F for 60 minutes
5. Cool at 4°F per minute

For 977-3 matrix composites the cure cycle is as follows:

1. Apply full vacuum
2. Apply 85 psi pressure, when pressure reaches 20 psi vent the vacuum
3. Heat to 355°F at 5°F per minute
4. Hold at 355°F for 360 minutes
5. Cool at 5°F per minute under 85 psi

Additional cure cycles for 977-3 matrix composites were performed free standing in an oven using the following cycle:

1. Heat to 355°F at 5°F per minute
2. Hold at 355°F for 360 minutes
3. Cool at 5°F per minute

Factor	Level 1	Level 2
Resin	3501-6	977-3
Fiber Form	AS4 (Uni.)	AS4 (Cloth)
Orientation	0°/45°/90°/-45°	0°/90°
Coating	None	Painted
Cure Cycle	Standard	Multiple
Thickness	16 Plies	48 Plies
Flux	Low	High
Time	15 Minutes	45 Minutes
Environ. Exp.	Ambient	0.85% H^2O

Table 1. Factors and Levels

Since the cloth chosen was a balance weave and a per ply thickness roughly double that of a prepreg layer, each cloth layer was treated like a two ply $\{\theta/\theta+90°\}$ prepreg layer, where θ is some orientation angle, which is reflected in several of the factors. For prepreg, one of the orientations was $(0/45/90/135)_{ns}$, where as for cloth the similar orientation was $(\{0/90\}\{45/135\})_{ns}$. Differences in the bending strength of these laminates were not a problem, since the heat damage strength was normalized to a control of the same laminate type. Since the cloth cured per ply thickness was roughly twice that of a prepreg ply, 1/2 the number of cloth plies were used as for the prepreg laminates to maintain an equivalent thickness laminate. For example, the lower level of thickness for prepreg laminate is 16 plies, while cloth laminates made at the lower level of thickness were only 8 plies.

The factor "Time" is the amount of time after start of the radiant quartz lamps bank. For a dry laminate roughly after the first 4-6 minutes a relatively steady state near front surface temperature is reached (this will be discussed further in the experimental procedures Section 4.1).

Our quartz lamp exposure facility is primarily set up to do very rapid heating conditions. For the low levels of flux used, the flux meter to measure the radiant energy produced did not work accurately. As a result, a direct measurement of the two flux levels was not able to be obtained with our equipment. Though flux level was able to be controlled accurately by controlling the voltage going to the quartz lamp bank. Thus, the high and low levels of flux were repeatable even though they were not measured directly.

The factor "Environmental Exposure" at the low level is at ambient conditions and at 0.85% +/-0.05% moisture content by weight. Humidity exposure conditions were at 160°F and 95% Relative Humidity.

3.2 SELECTION OF MEASURE OF MERIT

For a design of experiments, it is important to have a measure of merit that is sensitive to the effect being examined, and not having a large amount of error. An initial small scale experiment helped identify which measure of merit to use. This experiment consisted of 4-runs. The low flux/ low time condition resulted in little heat damage done to the panel. The high flux/ low time and low flux/ high time exposure resulted in moderate heat damage. The high flux/high time exposure resulted in severe heat damage. Figure 2 shows the location of the thermocouples. Figure 3 shows the method of thermocouple placement in the panels. This method of applying thermocouples produced reliable temperature measurement results. The only problems encountered was when the thermocouple bead slipped loose from the small hole that it was pressed into. Careful panel handling, i.e., preventing loading of the thermocouple bead by potting it into place with sealant and supporting the thermocouple wire leads during exposure, prevented this type of failure. Application of thermocouples directly to the panel surface was found to be unsuitable due to direct radiant heating of the thermocouple bead, which resulted in an inaccurate measurement of the panel surface temperature. The use of optical pyrometers overestimated the panel surface temperature, most likely due to the reflection of radiant energy from the panel surface. Table 2 shows the equilibrium measured temperatures during exposure.

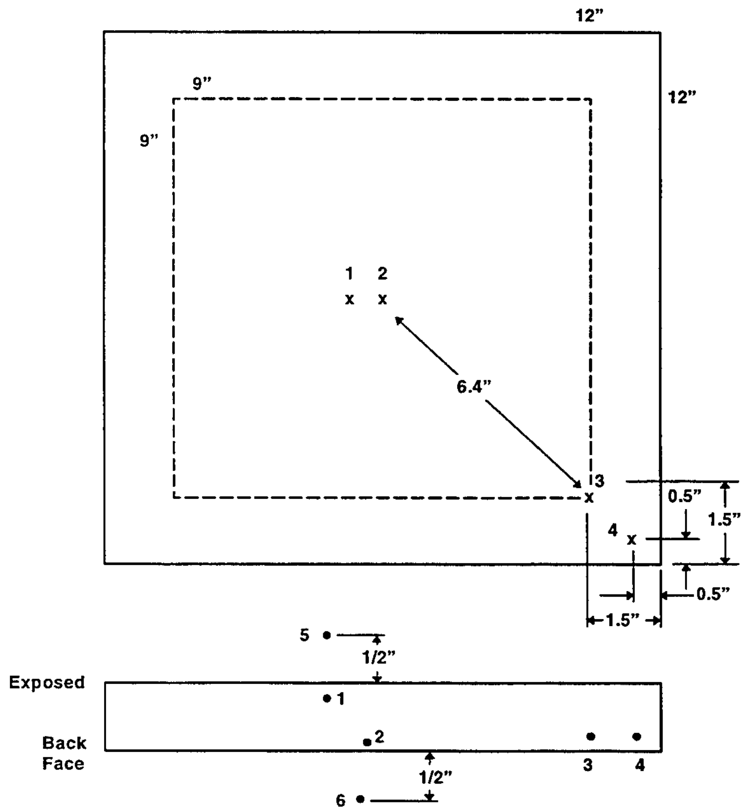


Figure 2. Thermocouple Locations

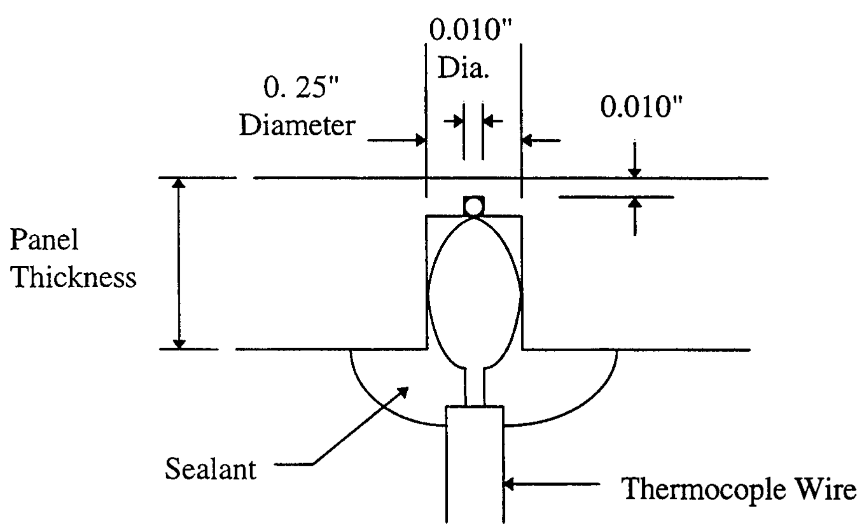


Figure 3. Method of Thermocouple Attachment

Table 2. Measure of Merit Panel Exposures Temperature Data

Panel #	Time to Equilibrum (minutes)		Thermocouple Location 1	2	3	4	5	6
D-2	6.1	Temperature Range after Equilibrum (°F)	483 to 486	459 to 464	455 to 456	390 to 390	223 to 221	118 to 121
		Median	485	462	456	390	222	120
		Change from Backside Thermocouple	23	0	-6	-72		
D-4	6.8	Temperature Range after Equilibrum (°F)	528 to 539	497 to 508	491 to 497	419 to 424	241 to 243	125 to 130
		Median	534	503	494	422	245	128
		Change from Backside Thermocouple	31	0	-9	-81		
E-2	6.35	Temperature Range after Equilibrum (°F)	530 to 537	504 to 511	498 to 498	427 to 427	245 to 248	127 to 130
		Median	534	508	498	427	247	129
		Change from Backside Thermocouple	26	0	-10	-81		
E-4	6.68	Temperature Range after Equilibrum (°F)	481 to 498	461 to 480	454 to 455	376 to 380	230 to 223	118 to 123
		Median	490	471	455	378	234	121
		Change from Backside Thermocouple	19	0	-26	-93		

After exposure the four 12"X12" panels were machined into four point shear, four point flexure at 24:1 and 32:1 span to depth ratios, and open-hole compression specimens. All specimens were nominally 0.5" in width, the open-hole compression had a 1/8" diameter hole and a 0.5" gage length and a 2" platen separation. All mechanical tests were performed at ambient conditions. The number of specimens ran were 8 to 10 and results are presented in Appendix A. The results for all specimens are summarized in Table 3, and for only nondelaminated specimens in Table 4. Figure 4 graphically shows the percentage strength retained for all tests. For a test to be sensitive to heat damage the strength should drop off rapidly for low to moderate heat damage. The four point shear test is seen to be much more sensitive than the other tests for detecting heat damage. Figure 5 graphically depicts the ratio of standard deviation and the heat damaged strength expressed as a percentage. All tests showed comparable results with low relative standard deviations (3-7.3%) for low to moderate heat damage, and high relative standard deviation (22.8-35.7%) for severe heat damage. No test method appeared to be superior in regard to relative error. Thus, as a result of this study the four-point shear test was selected as a measure of merit. The 24:1 flexure test was selected as a second measure of merit, since it was beneficial to have a measure of merit which could exhibit multiple failure modes. The flexure test has the capability of failure in compression on the compressive loaded side, tension on the tensile loaded side, or by shear in the mid-plane. Thus, as a result of this study, two measures of merit were selected, the four-point shear and the four-point flexure at 24:1 span-to-depth ratio.

3.3 EXPERIMENTAL DESIGN

In an experimental design early identification of which interactions that may be important is required, since the design developed needs to be able to separate these interactions. If two interactions are not separable they are said to be confounded. The goal of the experimental design is not to confound factors or interactions which were identified as important. In Figure 6, the interactions that were considered significant are identified; the rows and column labels are the main effects, at the intersection of a row and column is an interaction. The interactions on Figure 6 are the ones that the Adhoc Committee on Heat Damage decided may be significant. Thus, the experimental design should be set-up to separate out these interactions. For the experimental design and data analysis a computer program "Statgraphics Plus for Windows" by Manugistics, was found to be useful to help setup the design and analyze the data. In Figure 7, the experimental design developed successfully separated all interactions identified. One identified interaction, DI (time-environmental exposure), was confounded with a nonidentified interaction, AH (thermal history-fiber form), otherwise the design was very clean. Additionally, 12 two-level interactions that were not identified as important are separable. For the 64-run experiment, 21 columns did not contain primary factors or two level interactions, and therefore only contained higher order interactions. Since higher order interactions are usually not considered as important, these columns were used for an estimate of error. Since, the measure of merit was easy to replicate, at least five flexure

Table 3. Summary of Test Results for the Measure of Merit Determination

Test Method	Temperature Goal (°F)	Exposure Time (Minutes)	Virgin Strength (KSI) σ_{virgin}	Virgin Standard Deviation (KSI) δ_{virgin}	Exposed Strength (KSI) $\sigma_{exposed}$	Exposed Standard Deviation (KSI) $\delta_{exposed}$	Ratio of Exposed Standard Deviation to Strength $\%\delta_{exposed}/\sigma_{exposed}$	Ratio of Exposed to Virgin Strength $\%\sigma_{exposed}/\sigma_{virgin}$
Four-Point	480	15	9.06	0.4	7.07	0.66	9.3	78.0
Shear	480	45			5.31	0.64	12.1	58.6
16 to 1	510	15			5.45	0.29	5.3	60.2
Span-to-Depth Ratio	510	45			2.41	0.68	28.2	26.6
Four-Point	480	15	137.4	6.3	123.9	5.3	4.3	90.2
Flexure	480	45			114.4	19.3	16.9	83.3
24 to 1	510	15			118.8	17.7	14.9	86.5
Span-to-Depth Ratio	510	45			36	11.6	32.2	26.2
Four-Point	480	15	126.6	3.1	121.6	6.1	5.0	96.1
Flexure	480	45			119.4	5.6	4.7	94.3
32 to 1	510	15			110.8	16.2	14.6	87.5
Span-to-Depth Ratio	510	45			36.7	10.7	29.2	29.0
Open-Hole	480	15	53.1	2	51.8	2	3.9	97.6
Compression	480	45			47.7	8.1	17.0	89.8
	510	15			45.1	15.5	34.4	84.9
	510	45			14.1	5.2	36.9	26.6

Table 4. Summary of Test Results for the Measure of Merit Determination (Non-delaminated Specimens Only)

Test Method	Temperature Goal (°F)	Exposure Time (Minutes)	Virgin Strength (KSI) σ_{virgin}	Virgin Standard Deviation (KSI) δ_{virgin}	Exposed Strength (KSI) $\sigma_{exposed}$	Exposed Standard Deviation (KSI) $\delta_{exposed}$	Ratio of Exposed Standard Deviation to Strength $\%\delta_{exposed}/\sigma_{exposed}$	Ratio of Exposed to Virgin Strength $\%\sigma_{exposed}/\sigma_{virgin}$
Four-Point	480	15	9.06	0.4	7.11	0.41	5.8	78.5
Shear	480	45			5.58	0.41	7.3	61.6
16 to 1	510	15			5.43	0.3	5.5	59.9
Span-to-Depth Ratio	510	45			2.51	0.78	31.1	27.7
Four-Point	480	15	137.4	6.3	123.2	4.2	3.4	89.7
Flexure	480	45			119.2	3.3	2.8	86.8
24 to 1	510	15			123.9	7.6	6.1	90.2
Span-to-Depth Ratio	510	45			37.8	13.5	35.7	27.5
Four-Point	480	15	126.6	3.1	123.1	5.4	4.4	97.2
Flexure	480	45			119	5.8	4.9	94.0
32 to 1	510	15			114.3	6.7	5.9	90.3
Span-to-Depth Ratio	510	45			34.2	7.8	22.8	27.0
Open-Hole	480	15	53.1	1.3	51.7	2.0	3.9	97.3
Compression	480	45			51.4	2.0	3.9	96.8
	510	15			52.3	1.6	3.0	98.6
	510	45			15.8	4.5	28.8	29.7

	30 Min @ 460 F	15 Min @ 480 F	45 Min @ 480 F	15 Min @ 510 F	45 Min @ 510 F
FPS 16:1	84.3	78.5	61.6	59.9	27.7
FPF 24:1	93.2	89.7	86.8	90.2	27.5
FPF 32:1	96.7	97.2	94	90.3	27
OHC		97.3	96.7	98.5	29.6

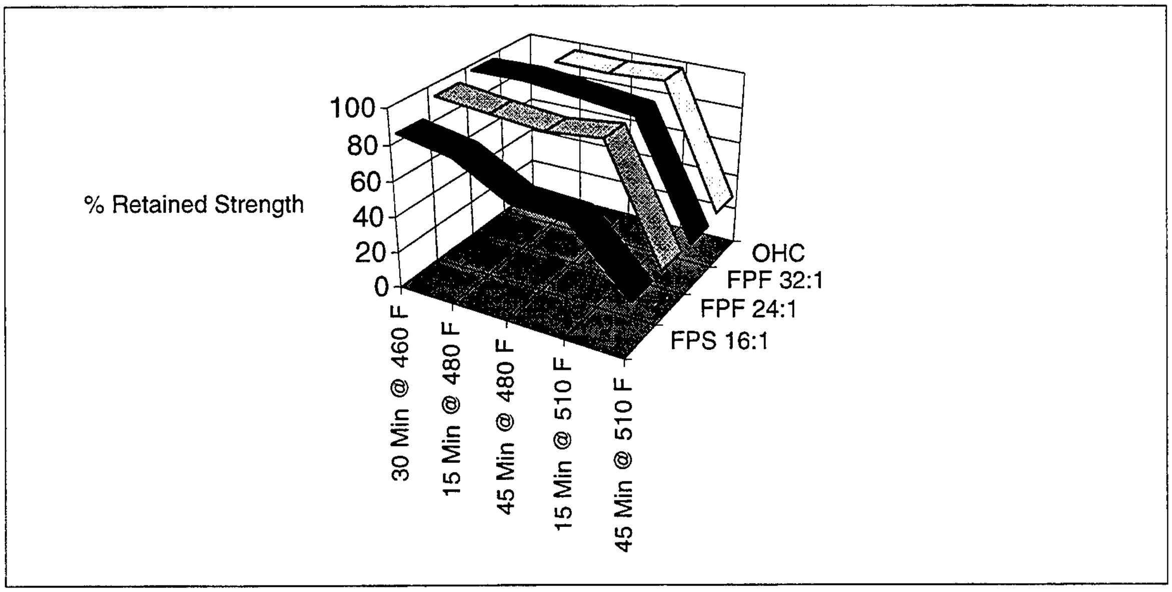


Figure # 4 Percent Retained Panel Strength after Heat Damage for Nondelaminated Specimens

	30 Min @ 460 F	15 Min @ 480 F	45 Min @ 480 F	15 Min @ 510 F	45 Min @ 510 F
FPS 16:1	6	5.8	7.3	5.5	31.1
FPF 24:1	4.2	3.4	2.8	6.1	35.7
FPF 32:1	4.2	4.4	4.9	5.9	22.8
OHC		3.9	3.9	3	28.8

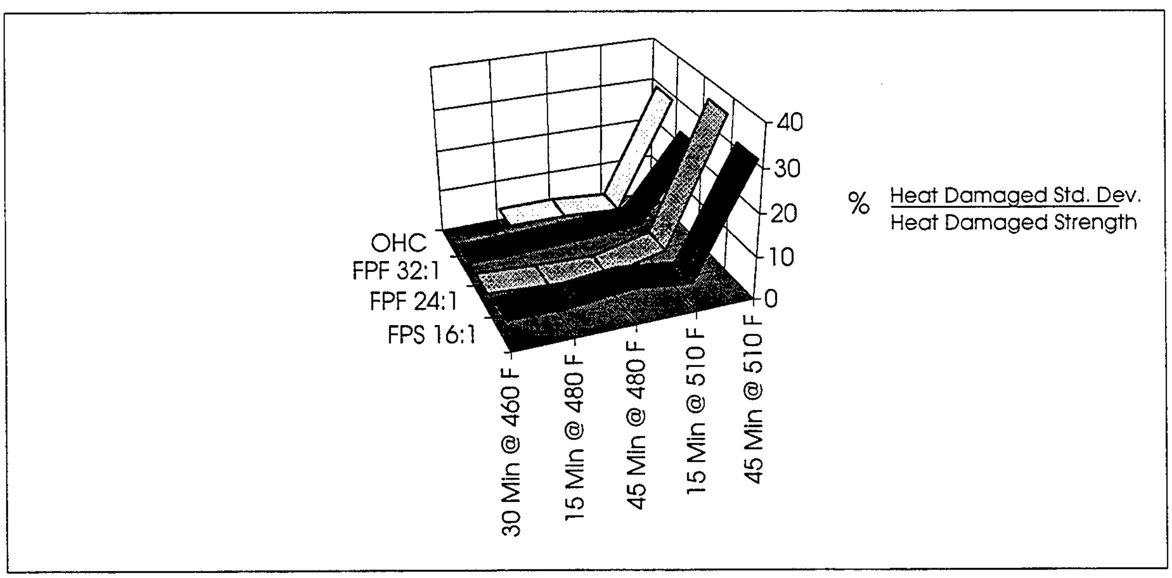


Figure # 5 Ratio of Heat Damaged Specimen's Standard Deviation to Strength for Nondelaminated Specimens (Expressed as a Percentage)

	A	B	C	D	E	F	G	H	I
(A) Thermal History		AB	AC						
(B) Thickness			BC		BE	BF	BG	BH	
(C) Resin				CD		CF			CI
(D) Time of Exposure					DE	DF			DI
(E) Coating						EF			EI
(F) Flux Level							FG	FH	FI
(G) Ply Orientation								GH	
(H) Fiber Form									
(I) Environ. Exposure									

Figure 6. Two Level Interaction Array

Factor Identification	Factor Name	Lower Level Setting	High Level Setting
A	Thermal History	one standard cure cycle	two additional simulated cure cycles free standing in an oven
B	Thickness	16 plies (prepreg) or 8 plies (cloth)	48 plies (prepreg) or 24 plies (cloth)
C	Resin	3501-6	977-3
D	Exposure Time	15 minutes	45 minutes
E	Coating	none	painted
F	Exposure Flux Level	low	high
G	Layup	$(0,45,90,135)_{ns}$ for prepreg and $(0/90,45/135)_{ns}$ for cloth	$(0,90)_{ns}$ for prepreg and $(0/90)_{ns}$ for cloth
H	Fiber Form	AS4 fiber unidirectional	AS4 fiber balanced weave cloth
I	Environmental Exposure	moisture weight gain of 0.85%	ambient conditions
AB	A Two-Level Interaction plus Higher Order Interactions		
AC			
AD+HI	Two Two-Level Interactions plus Higher Order Interactions		
AE	A Two-Level Interaction plus Higher Order Interactions		
AF			
AG			
AH+DI	Two Two-Level Interactions plus Higher Order Interactions		
AI+DH	Two Two-Level Interactions plus Higher Order Interactions		
BC	A Two-Level Interaction plus Higher Order Interactions		
BD			
BE			
BF			
BG			
BH			
BI			
CD			
CE			
CF			
CG			
CH			
CI			
DE			
DF			
DG			
EF			
EG			
EH			
EI			
FG			
FH			
FI			
GH			
GI			

Figure 7. Separable Main Factors and Two- Level Interactions

and five shear were tested per condition. This resulted in two methods to analyze the results. The first method is to use a 64-run design on the average of the five values. The second method is to use a design consisting of 5 replicates of the 64-run design or 320 individually entered values. By using the individually entered values an estimate of error within the group of measurements was able to be calculated directly. This resulted in the ability to calculate an F-ratio, which is the ratio of the variance explained by the factor or interaction to the unexplained variance. Larger F-ratios imply that these are more significant effects. Using an average value, the error is estimated as an average of the columns which do not have main effects or interactions assigned to them. For the 64-run design, 21 of the 64 columns may be used for the estimate of error. The design matrix for the average value is given in Table 5. Each row of this matrix consists of an experimental run. For each run the levels of the main factors are determined by the settings in this matrix.

Table #5 Experimental Design Matrix for Average Values

Panel #	Thermal History	Thickness (equivalent # of plies)	Resin	Time (minutes)	Coating	Flux Level	Layup	Fiber Form	Environmental Exposure
7D	none	16	3501-6	15	none	low	0/90	Cloth	Humidity
1C	3 Cures	16	3501-6	15	none	low	Quasi	Uni.	Humidity
6D	none	48	3501-6	15	none	low	Quasi	Cloth	Humidity
4C	3 Cures	48	3501-6	15	none	low	0/90	Uni.	Humidity
9D	none	16	977-3	15	none	low	Quasi	Uni.	Ambient
15D	3 Cures	16	977-3	15	none	low	0/90	Cloth	Ambient
12A	none	48	977-3	15	none	low	0/90	Uni.	Ambient
14B	3 Cures	48	977-3	15	none	low	Quasi	Cloth	Ambient
5B	none	16	3501-6	45	none	low	Quasi	Cloth	Ambient
3B	3 Cures	16	3501-6	45	none	low	0/90	Uni.	Ambient
8C	none	48	3501-6	45	none	low	0/90	Cloth	Ambient
2A	3 Cures	48	3501-6	45	none	low	Quasi	Uni.	Ambient
11D	none	16	977-3	45	none	low	0/90	Uni.	Humidity
13B	3 Cures	16	977-3	45	none	low	Quasi	Cloth	Humidity
10C	none	48	977-3	45	none	low	Quasi	Uni.	Humidity
16A	3 Cures	48	977-3	45	none	low	0/90	Cloth	Humidity
3A	none	16	3501-6	15	Painted	low	0/90	Uni.	Ambient
5C	3 Cures	16	3501-6	15	Painted	low	Quasi	Cloth	Ambient
2D	none	48	3501-6	15	Painted	low	Quasi	Uni.	Ambient
8D	3 Cures	48	3501-6	15	Painted	low	0/90	Cloth	Ambient
13C	none	16	977-3	15	Painted	low	Quasi	Cloth	Humidity
11A	3 Cures	16	977-3	15	Painted	low	0/90	Uni.	Humidity
16D	none	48	977-3	15	Painted	low	0/90	Cloth	Humidity
10A	3 Cures	48	977-3	15	Painted	low	Quasi	Uni.	Humidity
1B	none	16	3501-6	45	Painted	low	Quasi	Uni.	Humidity
7C	3 Cures	16	3501-6	45	Painted	low	0/90	Cloth	Humidity
4D	none	48	3501-6	45	Painted	low	0/90	Uni.	Humidity
6B	3 Cures	48	3501-6	45	Painted	low	Quasi	Cloth	Humidity
15B	none	16	977-3	45	Painted	low	0/90	Cloth	Ambient
9B	3 Cures	16	977-3	45	Painted	low	Quasi	Uni.	Ambient
14A	none	48	977-3	45	Painted	low	Quasi	Cloth	Ambient
12C	3 Cures	48	977-3	45	Painted	low	0/90	Uni.	Ambient
3C2	none	16	3501-6	15	none	high	0/90	Uni.	Ambient
5D	3 Cures	16	3501-6	15	none	high	Quasi	Cloth	Ambient
2B	none	48	3501-6	15	none	high	Quasi	Uni.	Ambient
8B	3 Cures	48	3501-6	15	none	high	0/90	Cloth	Ambient
13A	none	16	977-3	15	none	high	Quasi	Cloth	Humidity
11B	3 Cures	16	977-3	15	none	high	0/90	Uni.	Humidity
16B	none	48	977-3	15	none	high	0/90	Cloth	Humidity
10B	3 Cures	48	977-3	15	none	high	Quasi	Uni.	Humidity
1D	none	16	3501-6	45	none	high	Quasi	Uni.	Humidity
7B	3 Cures	16	3501-6	45	none	high	0/90	Cloth	Humidity
4B	none	48	3501-6	45	none	high	0/90	Uni.	Humidity
6C	3 Cures	48	3501-6	45	none	high	Quasi	Cloth	Humidity
15C	none	16	977-3	45	none	high	0/90	Cloth	Ambient
9C	3 Cures	16	977-3	45	none	high	Quasi	Uni.	Ambient
14C	none	48	977-3	45	none	high	Quasi	Cloth	Ambient
12B	3 Cures	48	977-3	45	none	high	0/90	Uni.	Ambient
7A	none	16	3501-6	15	Painted	high	0/90	Cloth	Humidity
1A	3 Cures	16	3501-6	15	Painted	high	Quasi	Uni.	Humidity
6A	none	48	3501-6	15	Painted	high	Quasi	Cloth	Humidity
4A	3 Cures	48	3501-6	15	Painted	high	0/90	Uni.	Humidity
9A	none	16	977-3	15	Painted	high	Quasi	Uni.	Ambient
15A	3 Cures	16	977-3	15	Painted	high	0/90	Cloth	Ambient
12D	none	48	977-3	15	Painted	high	0/90	Uni.	Ambient
14D	3 Cures	48	977-3	15	Painted	high	Quasi	Cloth	Ambient
5A	none	16	3501-6	45	Painted	high	Quasi	Cloth	Ambient
3D	3 Cures	16	3501-6	45	Painted	high	0/90	Uni.	Ambient
8A	none	48	3501-6	45	Painted	high	0/90	Cloth	Ambient
2C	3 Cures	48	3501-6	45	Painted	high	Quasi	Uni.	Ambient
11C	none	16	977-3	45	Painted	high	0/90	Uni.	Humidity
13D	3 Cures	16	977-3	45	Painted	high	Quasi	Cloth	Humidity
10D	none	48	977-3	45	Painted	high	Quasi	Uni.	Humidity
16C	3 Cures	48	977-3	45	Painted	high	0/90	Cloth	Humidity

4.0 Experimental Procedure

Four factors determined which constituents and lay-up should be used namely thickness, resin, lay-up, and fiber form. For each of these factors, 1/2 the panels are made at each of the settings. These four factors required that 2^4 or 16 different types of panels needed to be fabricated. The size of these panels was chosen to be 48"X48". This was to insure that four panels roughly 11.75"X11.75" could be cut from each of the larger panels. This process produced the 64 panels needed for the experimental design. The laminates were processed using the autoclave cure cycles described in Section 3.1. After cure, the panels were inspected with an ultrasonic C-scan.

4.1 Method of Thermal Exposure

The Tri-Services Thermal Radiation Test Facility at Wright-Patterson Air Force Base was used to thermally expose the panels required for this experiment. This facility was developed to simulate high level, i.e., nuclear flash types of heating rates. The problem that was encountered with the low power level exposures under this effort, was to control the lamp flux at these low levels. The quartz lamp bank used is computer controlled. This same computer is also used to collect and analyze data such as the control voltage to the lamps, thermocouple temperatures, and exposure time. During initial trials, it was found that controlling the control voltage to the quartz lamp bank is not sufficient. The lamp voltage and produced flux varied at a constant control voltage. Since the computer could not directly control the lamp voltage, the lamp voltage was initially recorded at the two required levels of control voltage used for this study. During subsequent runs, the lamp control voltage was checked at least once a day for each of the two levels used, and was recorded for each exposure. This method was found to produce reliable levels of flux from the quartz lamp bank.

It was desirable to produce a uniformly heat exposed panel, so specimens taken from different regions of this panel were exposed to the same heat damage. If this could be achieved, then multiple specimens could be tested from the same panel to get an idea of the scatter in the results. The standard flat lamp bank was found to not produce a uniform flux all the way across the panel. To obtain a more uniform flux distribution, a lamp bank in a Three-Tiered Quartz Lamp Bank (TTQLB) arrangement, as shown in Figure 8, was developed. This arrangement was comprised of a group of 12 8000-watt, 480-VAC tungsten filament, quartz lamps. The TTQLB is assembled as three layers or tiers of four lamps each on a horizontal plane. The bottom tier crosses two sets of lamps near the ends of their lighted length as to form a square 13 inches per side. Careful positioning of the lamps in each tier and the distance between tiers has yielded a fairly even flux distribution over a 12 by 12 inch square surface area. The TTQLB is mounted in a framework that is open above and below the lamps. The exposure arrangement for the panels as is shown in Figure 9. To minimize heat transfer, the panel was placed in a horizontal arrangement, and supported by three adjustable height nail points

The TTQLB is mounted inside a walk-in test chamber. Air flow throughout the chamber from bottom to top can be controlled with a variable speed fan to carry away any

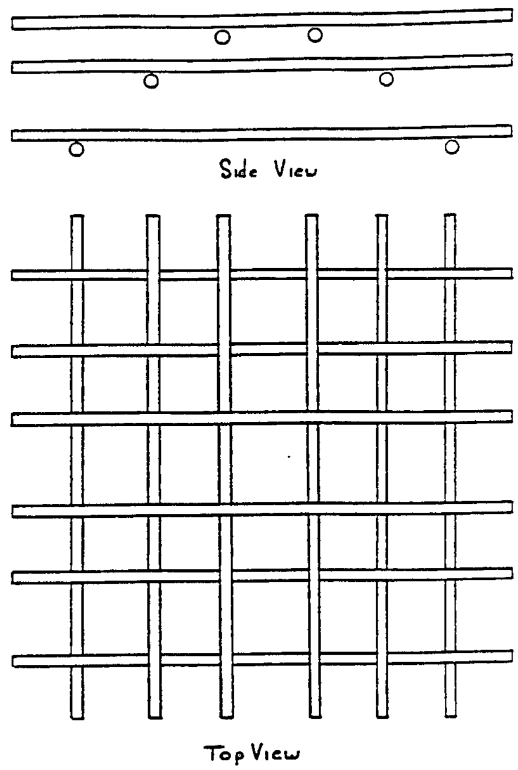


Figure 8. Three Tiered Quartz Lamp Bank

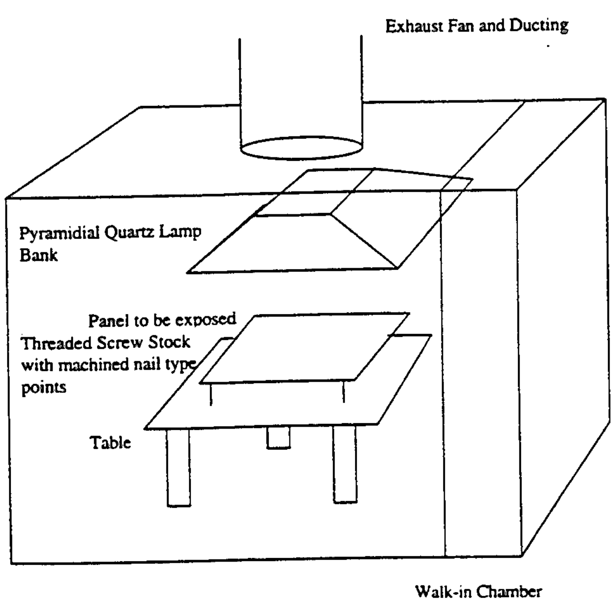


Figure 9. Quartz Lamp Exposure Chamber

smoke and fumes produced, but to not adversely cool the test sample. Ambient air temperature above and below the panels was monitored on some of the tests.

The test sample temperature was closely monitored using computer software that scans and records multiple thermocouples. This software was also capable of controlling the panel temperature off of a selected thermocouple. This capability was used for the four panel run experiment. For the 64-run experiment the panels were rather controlled to one of two chosen flux levels by using a specific control voltage.

To determine the required panel size, an experiment using 8"X8", 10"X10", and 12"X12" panels was conducted to see which size panel produced the most consistent temperature profile across the surface. The 12"X12" panel was found to produce the most uniform temperature profile during this test. In Figure 10, the temperature profile on the surface of the panel dropped rapidly at the corners of the panel, but is fairly uniform within a 10"X10" square in the center of the panel. All panels used in the experimental design were manufactured as 24"X24" panels and then trimmed and cut into panels approximately 11.75"X11.75" panels for exposure. The test specimens were cut out of a 10"X10" center portion of each panel. A summary of the exposure equilibrium temperatures is given in Appendix B.

4.2 MECHANICAL TESTING

Two mechanical test methods were used for the measure of merit, a 24:1 span to depth ratio four-point flexure, and a 16:1 span to depth ratio four-point shear test. In Section 3.2, these methods were found to be sensitive to detecting heat damage. The four-point shear test is described in Ref. 1. The four-point flexure test is described in ASTM D-790. Both of these tests load the specimens in a flexure mode. An Instron test machine with a crosshead loading rate of 0.10 inches per minute was used for both tests. Specimen width is 1/2". At least five specimens for each test method were tested from each panel. From the ultimate load, an ultimate strength was calculated as follows:

For Four-Point Shear:

$\sigma = .75P/bd$, where

σ=Ultimate Shear Strength
P=Ultimate Load
b=Specimen Width
d=Specimen Thickness

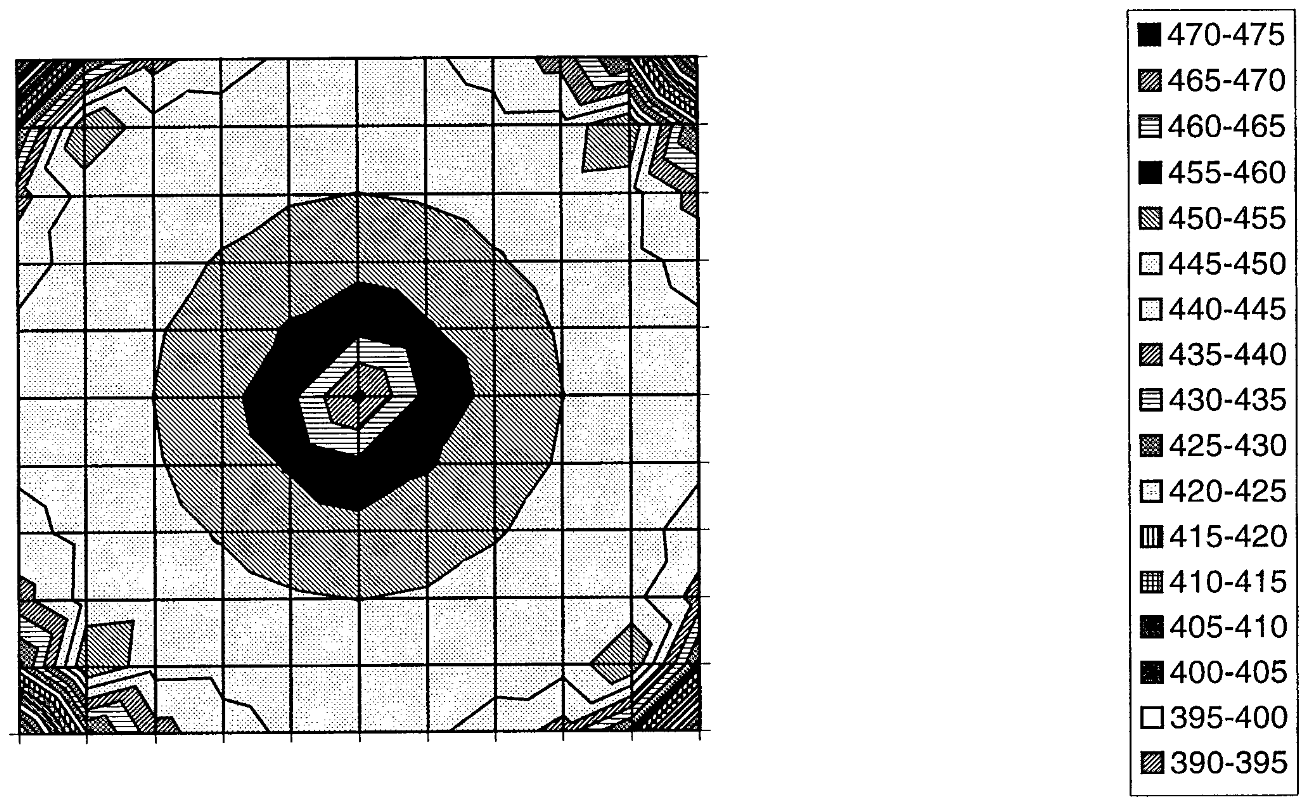
For Four-Point Flexure:

$S = PL/bd^2$, where

S=Maximum Stress in the Outer Fiber
L=Support Span

The test specimens were cut with a diamond saw. Cutting diagrams were developed for the thin (16 ply prepreg or 8 ply cloth) and the thick (48 ply prepreg or 24 ply cloth) laminates. The heat damaged surface was placed up in the test fixture, so that the radiantly heat exposed surface would be in compression. Some initial tests at UDRI showed that the orientation of the heat exposed surface influence the failure location. For 32:1 span to depth flexure specimens which failed on the tensile face undamaged, failed on the compression face if the radiantly heat exposed surface is placed upward

Figure 10. Near Surface Temperature under Radiantly Heated Face



(compressively loaded face). Since compression depends on the polymeric matrix to stiffen the fibers, this orientation produced better sensitivity to heat damage. For the flexure test, three primary modes of failure may occur; compression failure on the upper or compressively loaded face, tensile failure on the lower or tensile loaded face, or shear failure between plies. For the mechanical tests, the failure mode was recorded. All tests were performed at ambient conditions. The fixture has loading done with 0.25" diameter loading pins.

4.3 DATA REDUCTION

In Section 4.2, the method to calculate the mechanical strength was explained. This section will explain the data reduction required to use the measured strength in the design of experiments data analysis as a measure of merit. Due to the fact that some factors such as fiber form, orientation, resin and number of plies differ, the flexure or shear strength may vary so control undamaged panels were tested. The heat damaged panel's properties where normalized to the corresponding undamaged panels. This resulted in a fraction of the remaining undamaged strength. For example 0.5 means 50% of the undamaged laminate strength remains. Table 6 presents the results for four point shear testing and 24:1 span-to-thickness flexure testing. For the shear strength, all radiantly exposed panels do not have strengths greater than the control panels, beyond that allowed by the standard deviation errors. For the flex testing, several panels showed significant increases beyond that accounted for by the standard deviation differences. These panels are 3B, 3A, 8D, 11A, 1B, 9B, and $3C_2$. Three of these panels are normalized to the same control panel C3 namely 3B, 3A, and $3C_2$.

4.4 DATA ANALYSIS

A software package Statgraphics Plus for Windows by Manugistics, is used for the design of experiments analysis. This program allowed the data to be entered as replicates. For the first data analysis, five individual data points per panel were entered. The advantage of entering the data in this way is that variance explained by the factor may be ratioed to the unexplained variance to produce an F-ratio. A higher F-ratio indicates a more significant effect. Another way the data was entered is by using the five specimen average retained residual strength. The problem with this method is that the estimate of error is produced by estimating the error from columns of the design which are not assigned a main effect or a significant two level interaction. An advantage to entering the data in this way is that by looking at the magnitude of the error columns, you may get a idea if any significant factors such as other two level interactions or potentially significant three level interactions were mistakenly ignored. Another advantage of entering the averaged value is that this is a mean of five individual tests, so this value should be less affected by random error due to specimen defects or mechanical testing errors such as specimen or loading fixture misalignment.

Two mechanical tests where utilized, the four-point shear test and the 24:1 span-to-depth ratio flexure test. Since these tests evaluate different mechanical failure modes of the composite, data from both tests where analyzed.

Table # 6 Normalized Shear and Flexure Data

Panel	Four-Point Shear Control Strength	Heat Damaged Strength for Four-Point Shear	% Shear Strength Retained	Four-Point Flexure Control Strength	Heat Damaged Strength for Four-Point Flexure	% Flexure Strength Retained
7D	8211	1787	21.76	154469	86054	55.71
1C	9059	5961	65.80	132149	134795	102.00
6D	5378	4593	85.40	83582	70730	84.62
4C	8352	6061	72.57	140675	88158	62.67
9D	7974	8369	104.95	123967	121903	98.33
15D	8876	8266	93.13	140979	134417	95.35
12A	8289	8531	102.92	140276	144158	102.77
14B	5598	5069	90.55	86631	81362	93.92
5B	7801	5764	73.89	118747	111135	93.59
3B	10287	6308	61.32	121524	165027	135.80
8C	7297	6780	92.91	118042	115098	97.51
2A	7366	7199	97.73	109139	95568	87.57
11D	10838	6526	60.21	173806	161391	92.86
13B	7391	2709	36.65	108853	51313	47.14
10C	7256	2291	31.57	104194	37728	36.21
16A	8170	3404	41.66	133599	48226	36.10
3A	10287	9172	89.16	121524	183739	151.20
5C	7801	6868	88.04	118747	119193	100.38
2D	7366	5231	71.02	109139	80717	73.96
8D	7297	7790	106.76	118042	125890	106.65
13C	7391	3160	42.75	108853	36966	33.96
11A	10838	7320	67.54	173806	197258	113.49
16D	8170	6708	82.11	133599	117521	87.97
10A	7256	6865	94.61	104194	108339	103.98
1B	9059	5025	55.47	132149	155709	117.83
7C	8211	5317	64.75	154469	141455	91.58
4D	8352	7473	89.48	140675	132987	94.54
6B	5378	3790	70.47	83582	59674	71.40
15B	8876	7011	78.99	140979	140696	99.80
9B	7974	6542	82.04	123967	135878	109.61
14A	5598	4521	80.76	86631	74817	86.36
12C	8289	8145	98.26	140276	139322	99.32
3C2	10287	7064	68.67	121524	160470	132.05
5D	7801	4590	58.84	118747	76603	64.51
2B	7366	6327	85.89	109139	100212	91.82
8B	7297	6875	94.22	118042	108961	92.31
13A	7391	1029	13.92	108853	19072	17.52
11B	10838	4460	41.15	173806	78284	45.04
16B	8170	3577	43.78	133599	56686	42.43
10B	7256	4437	61.15	104194	71392	68.52
1D	9059	2040	22.52	132149	46209	34.97
7B	8211	1525	18.57	154469	18166	11.76
4B	8352	3670	43.94	140675	70624	50.20
6C	5378	2900	53.92	83582	44404	53.13
15C	8876	4053	45.66	140979	56188	39.86
9C	7974	4048	50.76	123967	84781	68.39
14C	5598	3220	57.52	86631	47278	54.57
12B	8289	5607	67.64	140276	85909	61.24
7A	8211	4108	50.03	154469	44483	28.80
1A	9059	4166	45.99	132149	100491	76.04
6A	5378	4250	79.03	83582	63638	76.14
4A	8352	6840	81.90	140675	109565	77.89
9A	7974	5816	72.94	123967	126286	101.87
15A	8876	7245	81.62	140979	150464	106.73
12D	8289	8721	105.21	140276	138142	98.48
14D	5598	5156	92.10	86631	81256	93.80
5A	7801	4098	52.53	118747	72413	60.98
3D	10287	3045	29.60	121524	84162	69.26
8A	7297	4558	62.46	118042	66005	55.92
2C	7366	2438	33.10	109139	29802	27.31
11C	10838	3850	35.52	173806	41746	24.02
13D	7391	836	11.31	108853	16485	15.14
10D	7256	1968	27.12	104194	28782	27.62
16C	8170	1106	13.54	133599	19148	14.33

5.0 RESULTS AND DISCUSSION

5.1 RANKING OF SIGNIFICANT FACTORS AND INTERACTIONS FOR FLEXURE

The raw mechanical test data is provided as Appendix C. The results for the 24:1 flexure data for five data points entered as replicates is presented in Table 7. The largest F-ratio is the most significant effect. The associated P-Value gives an idea of the confidence limit as is shown in the following formula:

$$\text{Confidence Limit} = (1-P_{value})*100\%.$$

A P_{value} of 0.05 would indicate that this factor is significant to the 95% confidence limit. The ranking of the factors and interactions is graphically shown in Figure 11 as a Standard Pareto Chart. The standard error is shown as a light line parallel to the y axis. Table 8 shows the results of the 24:1 flexure testing with the data being entered as an average value of five data points. Figure 12 is the Standard Pareto Chart for the average normalized values for 24:1 flexure.

5.2 RANKING OF SIGNIFICANT FACTORS AND INTERACTIONS FOR SHEAR

Tables 7 and 8 show the results for four point shear testing for data entered as replicates and as average values respectively. Figures 13 and 14 are the Standard Pareto Charts of the four-point shear data entered as replicates and as average values respectively. For shear a mixed two level interaction occurred between time-thermal history and fiber form-environment exposure. This mixed interaction is most likely significant due to the effect of the fiber form-environmental exposure interaction, since both these factors are highly significant. However, without the ability to separate the two interactions, there is no way to know for certain.

5.3 DISCUSSION OF SHEAR AND FLEXURE RESULTS

Tables 7 and 8 show a summary ranking of all the factors and two level interactions for both the 24:1 flexure test and the four-point shear test. When the data is entered as an average value, versus being entered as replicates of individual data points, the order of the factors and interactions does not change, but the number of significant factors does change. The effect of time and flux, and the interaction of these two factors is fairly significant. Another big factor affecting heat damage is the effect of moisture aging or environmental exposure. This factor resulted in the panels showing some detectable blisters or delamination for the 0.85% moisture level examined. Thus, the moisture aged panels examined under this experiment did not produce a strength degradation without detectable damage (i.e., damage could always be detected). Fiber form is also a significant factor to both strength measures.

Table 7. Results of L64 for Heat Damage
(Five Specimens Treated as Replications of Runs)

Normalized Shear		Normalized Flex
I: Environ. Exposure		F: Flux
F: Flux		I: Environ. Exposure
D: Time		D: Time
G: Layup		H: Fiber Form
H: Fiber Form		BH
DF		DF
EI		C: Resin
AD+HI		BF
CI		BI
CG		GI
E: Coating		CI
EG		E: Coating
BF		G: Layup
CH	Significant Effects	AC
BI		BD
BC		EF
AG		AD+HI
DE		CE
BG		EI
B: Thickness		GH
CD		CD
AI+DH		FG
AF		FI
EH		AG
EF		B: Thickness
AH+DI		BC
GI		DE
BD		AI+DH
FH		BG
GH	95% Confidence Limit	AH+DI
DG		EG
BE		BE
AE		AB
BH		FH
CE		CF
FG		A: Thermal History
C: Resin		AE
CF		EH
AC		CH
A: Thermal History		AF
FI		DG
AB		CG

Table 8. Results of L64 for Heat Damage
(Data Entered as an Average of 5 Runs)

Normalized Shear		Normalized Flex
I: Environ. Exposure		F: Flux
F: Flux		I: Environ. Exposure
D: Time		D: Time
G: Layup		H: Fiber Form
H: Fiber Form	Significant Effects	BH
DF		DF
EI		C: Resin
AD+HI		BF
CI		BI
CG	95% Significance Level	GI
E: Coating		CI
EG		E: Coating
BF		G: Layup
CH		AC
BI		BD
BC		EF
AG		AD+HI
DE		CE
BG		EI
B: Thickness		GH
CD		CD
AI+DH		FG
AF		FI
EH		AG
EF		B: Thickness
AH+DI		BC
GI		DE
BD		AI+DH
FH		BG
GH		AH+DI
DG		EG
BE		BE
AE		AB
BH		FH
CE		CF
FG		A: Thermal History
C: Resin		AE
CF		EH
AC		CH
A: Thermal History		AF
FI		DG
AB		CG

Figure 11. Standard Pareto Chart for Flexure Data entered as Replicates

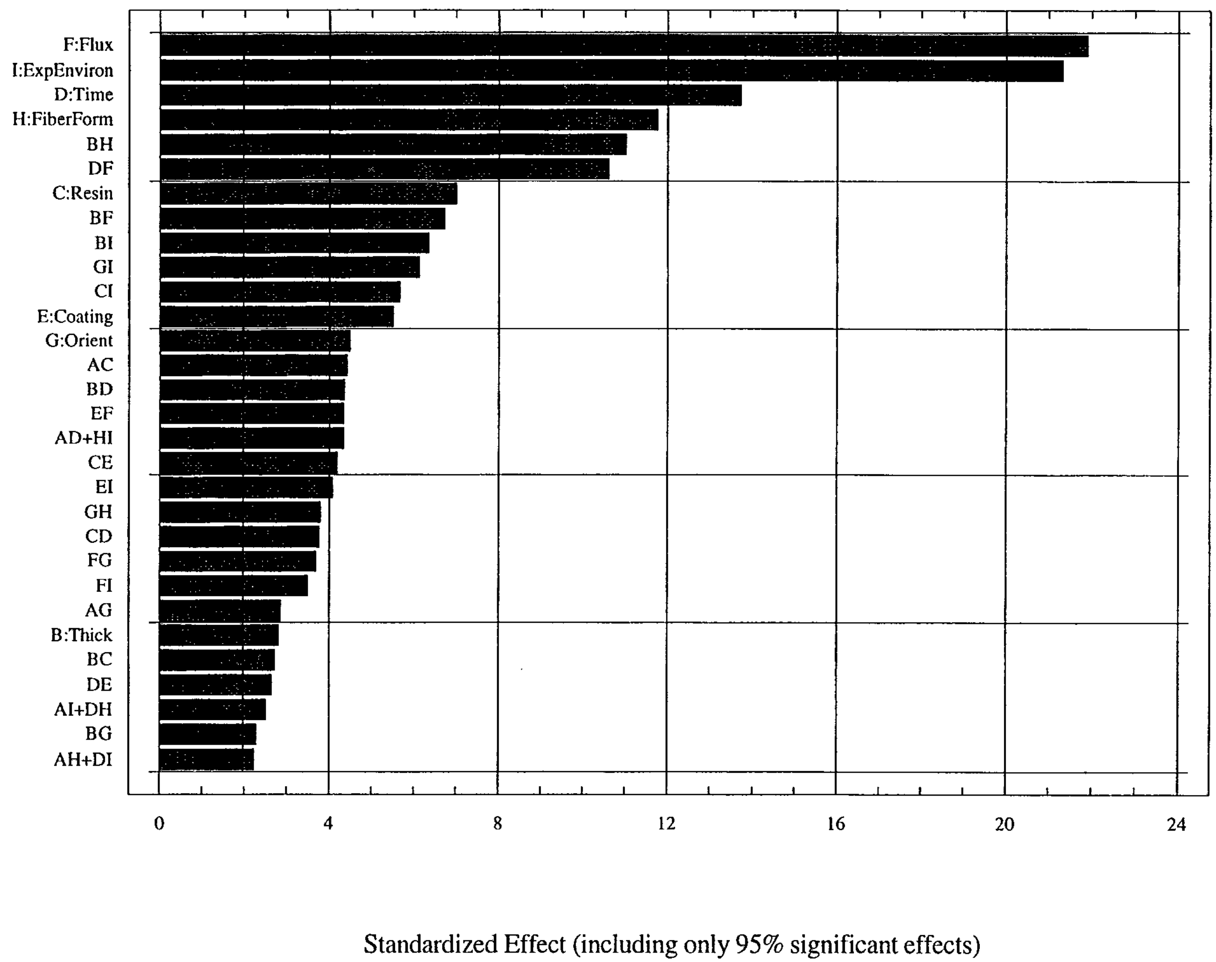


Figure 12. Standard Pareto Chart for Average Normalized Flexure Strength

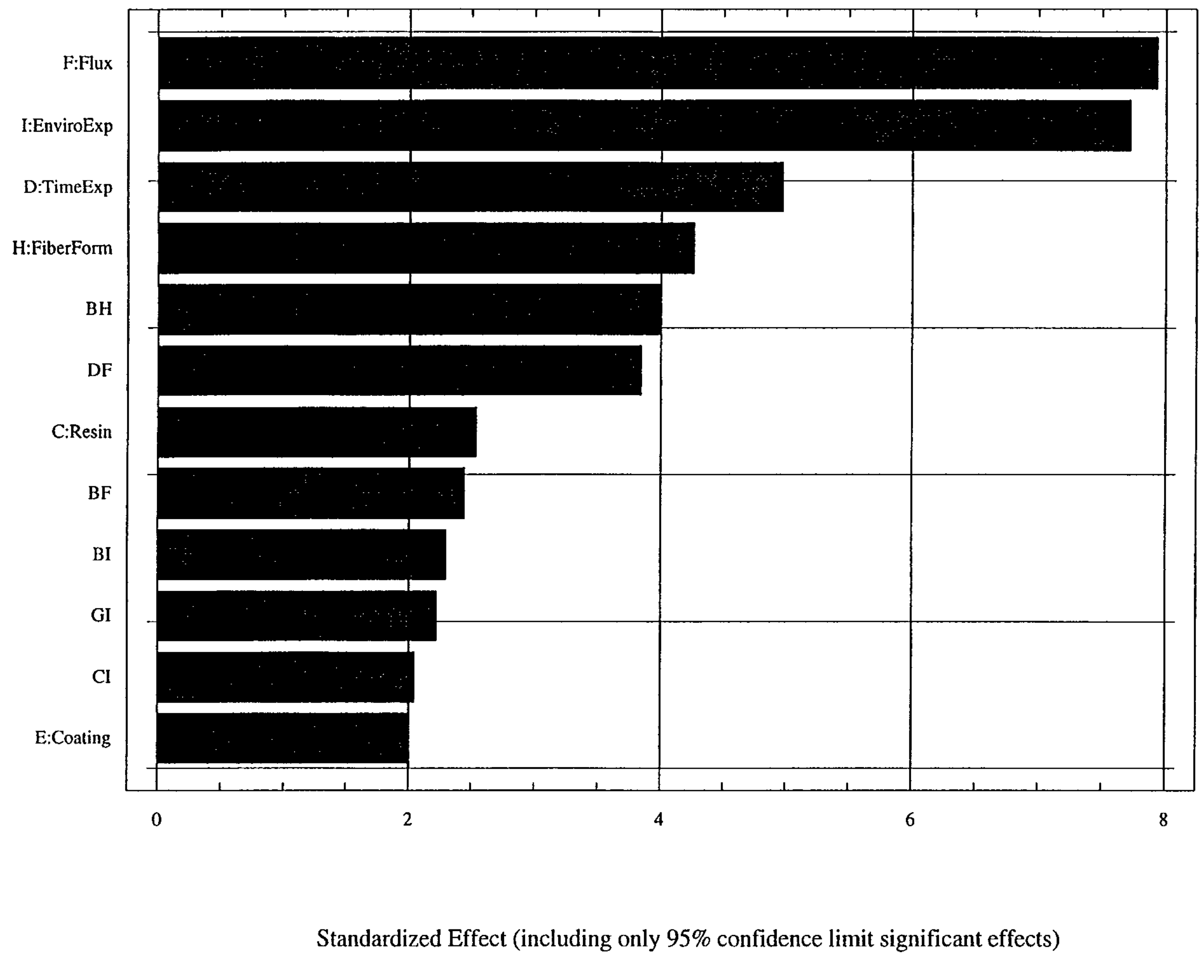


Figure 13. Standard Pareto Chart for Shear Data entered as Replicates

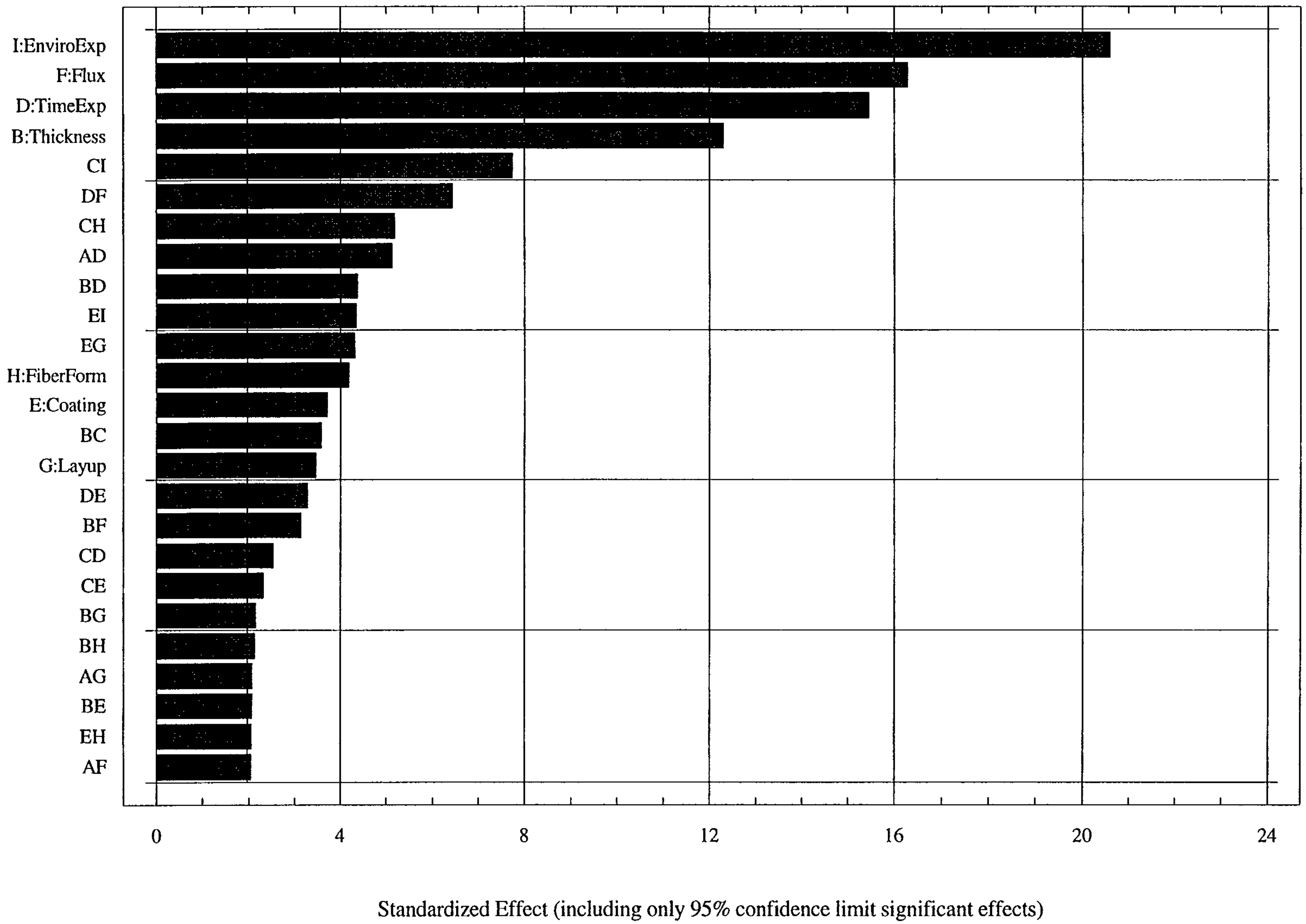


Figure 14. Standard Pareto Chart for Average Shear Strength

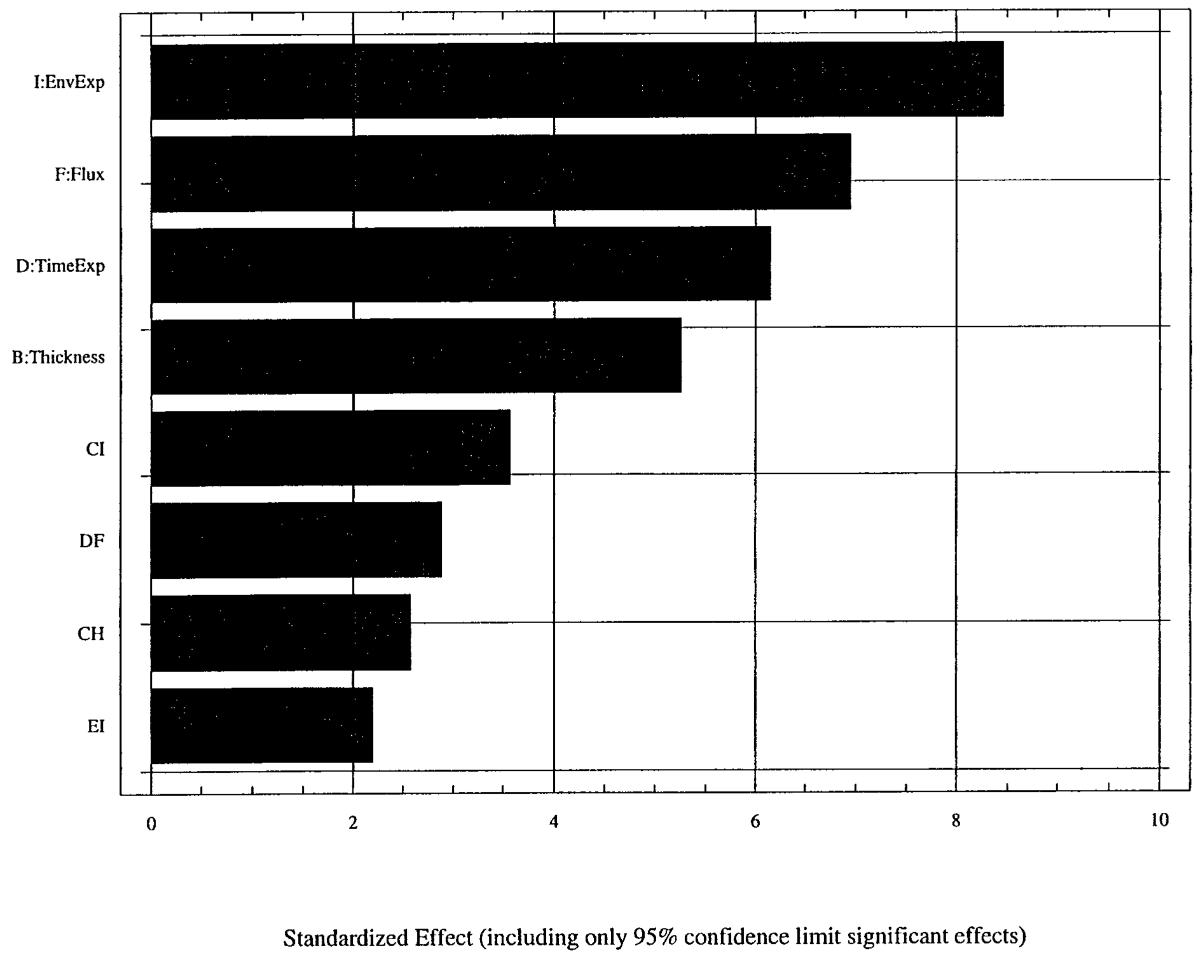


Table 9. Analysis of Variance for Normalized Average Flexure Test Results

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
A:ThermHist	0.00523262	1	0.00523262	0.25	0.6191
B:Thickness	0.0241521	1	0.0241521	1.18	0.2906
C:Resin	0.153391	1	0.153391	7.46	0.0125
D:TimeExp	0.590955	1	0.590955	28.75	0.0000
E:Coating	0.0944543	1	0.0944543	4.60	0.0439
F:Flux	1.50522	1	1.50522	73.24	0.0000
G:Layup	0.0627498	1	0.0627498	3.05	0.0952
H:FiberForm	0.433791	1	0.433791	21.11	0.0002
I:EnviroExp	1.42678	1	1.42678	69.42	0.0000
AB	0.00997025	1	0.00997025	0.49	0.4938
AC	0.0606739	1	0.0606739	2.95	0.1005
AD+HI	0.0584497	1	0.0584497	2.84	0.1065
AE	0.00508431	1	0.00508431	0.25	0.6241
AF	0.0027023	1	0.0027023	0.13	0.7205
AG	0.0252172	1	0.0252172	1.23	0.2805
AH+DI	0.0153369	1	0.0153369	0.75	0.3974
AI+DH	0.0195151	1	0.0195151	0.95	0.3409
BC	0.0230051	1	0.0230051	1.12	0.3021
BD	0.0589112	1	0.0589112	2.87	0.1052
BE	0.0114866	1	0.0114866	0.56	0.4630
BF	0.142375	1	0.142375	6.93	0.0156
BG	0.0161357	1	0.0161357	0.79	0.3856
BH	0.37979	1	0.37979	18.48	0.0003
BI	0.126087	1	0.126087	6.13	0.0218
CD	0.0441782	1	0.0441782	2.15	0.1574
CE	0.054409	1	0.054409	2.65	0.1186
CF	0.00687181	1	0.00687181	0.33	0.5693
CG	0.0000429861	1	0.0000429861	0.00	0.9640
CH	0.00340217	1	0.00340217	0.17	0.6882
CI	0.0996494	1	0.0996494	4.85	0.0390
DE	0.0216195	1	0.0216195	1.05	0.3167
DF	0.353251	1	0.353251	17.19	0.0005
DG	0.00201178	1	0.00201178	0.10	0.7575
EF	0.0587262	1	0.0587262	2.86	0.1058
EG	0.0117583	1	0.0117583	0.57	0.4578
EH	0.00454574	1	0.00454574	0.22	0.6430
EI	0.051648	1	0.051648	2.51	0.1279
FG	0.0422629	1	0.0422629	2.06	0.1663
FH	0.008397	1	0.008397	0.41	0.5296
FI	0.0377669	1	0.0377669	1.84	0.1896
GH	0.0447142	1	0.0447142	2.18	0.1551
GI	0.117393	1	0.117393	5.71	0.0263
Total error	0.431612	21	0.0205529		
Total (corr.)	6.64573	63			

R-squared = 93.5054 percent
R-squared (adjusted for d.f.) = 80.5163 percent
Standard Error of Est. = 0.143363
Mean absolute error = 0.0671836
Durbin-Watson statistic = 2.00293

Table 10. Analysis of Variance for Normalized Average Shear Test Results

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value	Estimated Effect (on Normalized Strength)
A:ThermHist	0.0022	1	0.0022	0.15	0.7112	0.01 +/- 0.03
B:Thickness	0.4310	1	0.4310	28.91	0.0000	0.16 +/- 0.03
C:Resin	0.0095	1	0.0095	0.64	0.4416	-0.02 +/- 0.03
D:TimeExp	0.5883	1	0.5883	39.47	0.0000	-0.19 +/- 0.03
E:Coating	0.0478	1	0.0478	3.21	0.0876	0.05 +/- 0.03
F:Flux	0.7506	1	0.7506	50.35	0.0000	-0.22 +/- 0.03
G:layup	0.0213	1	0.0213	1.43	0.2455	0.04 +/- 0.03
H:FiberForm	0.0298	1	0.0298	2.00	0.1720	-0.04 +/- 0.03
I:EnvExp	1.1157	1	1.1157	74.85	0.0000	-0.26 +/- 0.03
AB	0.0007	1	0.0007	0.05	0.8348	0.01 +/- 0.03
AC	0.0023	1	0.0023	0.15	0.7025	0.01 +/- 0.03
AD+HI	0.0598	1	0.0598	4.01	0.0583	-0.06 +/- 0.03
AE	0.0062	1	0.0062	0.42	0.5322	-0.02 +/- 0.03
AF	0.0156	1	0.0156	1.05	0.3182	-0.03 +/- 0.03
AG	0.0204	1	0.0204	1.37	0.2547	-0.04 +/- 0.03
AH+DI	0.0072	1	0.0072	0.49	0.5009	0.02 +/- 0.03
AI+DH	0.0092	1	0.0092	0.62	0.4491	0.02 +/- 0.03
BC	0.0520	1	0.0520	3.49	0.0757	-0.06 +/- 0.03
BD	0.0403	1	0.0403	2.70	0.1150	-0.05 +/- 0.03
BE	0.0033	1	0.0033	0.22	0.6478	-0.01 +/- 0.03
BF	0.0101	1	0.0101	0.68	0.4274	0.03 +/- 0.03
BG	0.0053	1	0.0053	0.35	0.5645	0.02 +/- 0.03
BH	0.0170	1	0.0170	1.14	0.2978	0.03 +/- 0.03
BI	0.0194	1	0.0194	1.30	0.2670	0.03 +/- 0.03
CD	0.0259	1	0.0259	1.74	0.2014	-0.04 +/- 0.03
CE	0.0080	1	0.0080	0.53	0.4807	0.02 +/- 0.03
CF	0.0028	1	0.0028	0.19	0.6730	-0.01 +/- 0.03
CG	0.0156	1	0.0156	1.04	0.3187	0.03 +/- 0.03
CH	0.1032	1	0.1032	6.92	0.0156	-0.08 +/- 0.03
CI	0.1979	1	0.1979	13.28	0.0015	-0.11 +/- 0.03
DE	0.0215	1	0.0215	1.44	0.2436	-0.04 +/- 0.03
DF	0.1294	1	0.1294	8.68	0.0077	-0.09 +/- 0.03
DG	0.0005	1	0.0005	0.03	0.8605	0.01 +/- 0.03
EF	0.0108	1	0.0108	0.73	0.4122	-0.03 +/- 0.03
EG	0.0393	1	0.0393	2.64	0.1193	0.05 +/- 0.03
EH	0.0140	1	0.0140	0.94	0.3534	0.03 +/- 0.03
EI	0.0750	1	0.0750	5.03	0.0358	0.07 +/- 0.03
FG	0.0003	1	0.0003	0.02	0.8963	0.00 +/- 0.03
FH	0.0039	1	0.0039	0.26	0.6193	0.02 +/- 0.03
FI	0.0003	1	0.0003	0.02	0.8872	0.00 +/- 0.03
GH	0.0183	1	0.0183	1.23	0.2806	-0.03 +/- 0.03
GI	0.0047	1	0.0047	0.32	0.5849	-0.02 +/- 0.03
Total error	0.3130	21	0.0149			
Total (corr.)	4.2494	63				

R-squared = 92.6338 percent
R-squared (adjusted for d.f.) = 77.9013 percent
Standard Error of Est. = 0.122089
Mean absolute error = 0.057383
Durbin-Watson statistic = 1.85925
Average Estimated Effect is 0.64 +/- 0.02

5.4 DISCUSSION OF FAILURE MODES

The failure mode is given in Appendix C for each panel. This section will briefly summarize the changes in failure mode with heat damage for both the shear and flexure results. For flexure, the unexposed control failure mode occurred by failure first on the compressively loaded face, followed by continued loading until ultimate failure occurred by tensile failure. For the control exposed panels, the 15 minute exposure at low power did not change the failure mode, but 45 minutes at low or high power did. For 45 minutes at high power, the failure mode was by delamination growth. For the four-point shear panels, the unexposed control failed by compression first under the load noses followed by ultimate failure in shear. For highly heat damaged panels, the failure mode switched to multiple shear failures.

6.0 CONCLUSIONS

This study has evaluated the heat damage of AS4/3501-6 and AS4/977-3 to determine which factors or two level interaction of factors most significantly affect the resulting strength degradation. Follow on efforts will be used to verify the results of this experiment by predicting the strength degradation of a composite panel exposed to conditions not experienced in this experiment. Also, this study may be expanded to include other composite materials. Further work is currently ongoing to attempt to detect heat degradation mechanisms with the panels from this experiment. Hopefully, a mechanism can be identified and nondestructive methods can be identified or developed to detect this mechanism. Remember that the ultimate goal of this effort is to develop a capability to go to a previously heat damaged aircraft and determine which area has an unacceptable level of strength remaining.

7.0 References

1. Browning, C.E., Abrams, F.L., and Whitney, J.M., "**A Four-Point Shear Test for Graphite/Epoxy Composites,**" *Composite Materials: Quality Assurance and Processing, ASTM STP 797,* C.E. Browning, Ed., American Society for Testing and Materials, 1983, pp. 54-74.

2. Pritt, H.L., "Thermal Degradation of Graphite/Epoxy Composites," Final Report Apr. 16 1979-Sep. 30 1980, Hercules Inc., Aerospace Division, Contract # N62669-79-C-0240, Report # NADC 78118-60, Nov 28 1980.

3. Pering, G.A., Farrell, P.V., and Springer, G.S., "Degradation of Tensile and Shear Properties of Composites Exposed to Fire or High Temperature," J. Composite Materials, Vol. 14 (Jan 1980), pp 54-68.

4. Street, K.N., Russell, A.J., Bonsang, F., "Thermal Damage Effects on Delamination Toughness of a Graphite/Epoxy Composite," Composites Science and Technology, Vol. 32 (1988), pp 1-14.

5. Griffis, C.A., Nemes, J.A., Stonesifer, F.R., and Chang, C.I., "Degradation in Strength of Laminated Composites Subjected to Intense Heating and Mechanical Loading," J. Composite Materials, Vol. 20 (May 1986), pp. 216-235.

6. Chen, J.K., Sun, C.T., "Failure Analysis of a Graphite/Epoxy Laminate Subjected to Combined Thermal and Mechanical Loading," J. Composite Materials, Vol. 19 (Sep. 1985), pp. 408-423.

7. Collings, T.A., Mead, D.L., "Effect of High Temperature spikes on a carbon fibre-reinforced epoxy laminate," Composites, Vol. 19, No. 1 (Jan 1988), pp. 61-66

8. Askins, D. Robert, "A Study of Overheat Damage to Structural Composites," 24th International SAMPE Technical Conference, Volume 24, Advanced Materials: Meeting the Economic Challenge; Edited by T.S. Reinhart, Malcolm Rosenow, Ray A. Cull, and Eddie Struckholt; 1992; pp. T806-T820.

Appendix A. Measure of Merit Test Data

Panel #	Four-Point Shear 16 to 1 Span-to-Depth Ratio Failure Strength (ksi)	Failure Mode	Four-Point Flexure 24 to 1 Span-to-Depth Ratio Failure Strength (ksi)	Failure Mode	Four-Point Flexure 32 to 1 Span-to-Depth Ratio Failure Strength (ksi)	Failure Mode	Open-Hole Compression Failure Strength (ksi)	Failure Mode
D-2	7.57	Shear	117.0	Tension	111.0	Tension	51.41	Compression @ Hole
	6.98	"	125.6	"	118.4	"	52.26	"
	7.27	"	125.8	"	121.3	"	55.63	"
	8.33	"	124.4	"	121.3	"	50.56	"
	7.32	"	122.0	"	126.9	"	52.03	"
	6.36	"	103.1	"	128.4	"	54.16	"
	6.40	"	118.9	"	128.1	"	49.23	"
	6.13	"	128.8	"	124.4	"	51.17	"
	7.42	"	122.4	Compression	114.3	"	50.10	"
	6.88	"	132.3	"				
			116.0	Tension				
D-4	3.59	Multiple Delaminations	63.6	Delamination	20.7	Delamination	9.90	Major Delaminations
	1.76	"	26.6	"	58.7	"	7.67	"
	2.12	"	37.9	"	35.3	"	24.45	Delamination
	2.49	"	42.0	"	32.4	"	13.25	"
	2.82	"	30.9	"	44.2	"	15.31	"
	3.00	"	45.3	"	31.4	"	17.97	"
	2.67	"	36.5	"	29.9	"	14.67	"
	2.31	"	36.8	"	36.4	"	14.73	"
	1.14	"	23.0	"	41.2	"	8.52	Delamination in Center Section
	2.22	"	27.6	"				
			25.6	"				
E-2	5.42	Shear under Load Noses	113.1	Delamination	115.9	Compression	52.87	Compression @ Hole
	5.64	"	126.8	"	112.1	"	53.19	"
	5.83	"	130.2	Compression	114.6	Compression/Tension	54.94	"
	5.13	"	126.3	Tension	117.0	"	52.98	"
	5.54	"	118.0	Delamination	100.9	Compression	50.77	"
	5.76	"	135.6	Compression	125.7	"	31.33	Compression Shear 1.5" from Hole
	5.21	"	69.9	Delamination	122.7	"	8.35	"
	5.57	"	131.5	"	71.9	Delamination	50.92	Compression @ Hole
	4.91	"	120.2	"	116.7	Tension	50.77	"
	5.49	"	114.8	"				
			120.6	Compression				

Panel #	Four-Point Shear 16 to 1 Span-to-Depth Ratio Failure Strength (ksi)	Failure Mode	Four-Point Flexure 24 to 1 Span-to-Depth Ratio Failure Strength (ksi)	Failure Mode	Four-Point Flexure 32 to 1 Span-to-Depth Ratio Failure Strength (ksi)	Failure Mode	Open-Hole Compression Failure Strength (ksi)	Failure Mode
E-4	5.37	End Delamination	132.9	Tension	129.0	Compression	55.23	Compression @ Hole
	3.88	Shear Under Grips	121.7	Delamination	120.6	Tension	40.05	Compression 1.5" from Hole
	5.25	End Delamination	58.4	Delamination	116.1	"	50.13	Compression @ Hole
	5.64	"	122.1	Tension	117.4	"	51.59	"
	6.08	"	117.0	Compression	123.1	"	29.23	Compression 1.5" from Hole
	5.21	Shear Under Grips	124.0	Tension	125.1	"	50.82	Compression @ Hole
	5.93	"	117.5	Delamination	117.8	Compression	50.38	"
	5.85	"	117.0	Tension	111.8	"	52.45	"
	4.95	End Delamination	112.5	Delamination	113.6	Tension	49.20	"
	4.96	Shear Under Grips	115.1	"				
			120.0	"				

Appendix B Panel Exposure Temperatures

Panel #	Front Center Temperature (°F)	Back Center Temperature (°F)	Front Corner Temperature (°F)	Back Corner Temperature (°F)	Time to Reach Equilibrum (Minutes)	Total Exposure Time (Minutes)	Flux Level
2B	550	474	516	448	14	15	High
14C	542	469	519	422	3.7	15	High
15C	484	481	513	469	6	45	High
9D	475	458	469	432	7.5	15	Low
5B	475	469	473	444	6	45	Low
8C	499	441	482	377	15	45	Low
12A	467	414	465	381	N/A	15	Low
3C	522	510	510	482	6	15	High
2D	491	432	399	470	N/A	15	Low
8A	537	469	522	436	15	45	High
12D	540	462	513	414	N/A	15	High
14A	514	454	492	407	17	45	Low
9A	541	521	514	478	6.5	15	High
15B	478	472	475	438	7	45	Low
5A	521	504	500	478	5	45	High
3A	480	473	458	432	5	15	Low
12B	564	471	541	441	18	45	High
14B	493	413	479	392	N/A	15	Low
8B	546	471	538	452	N/A	15	High
2A	511	441	487	414	14	45	Low
9C	540	504	525	488	7	45	Low
15D	497	467	482	446	6.5	15	Low
3B	497	468	476	455	5	45	Low
5D	534	503	526	498	5	15	High
12C	502	427	478	394	45	450	Low
14D	536	454	511	424	13.5	15	High
2C	567	482	536	451	15	45	High
8D	491	434	475	406	14.5	15	Low
3D	542	507	514	485	5	45	High
9B	492	469	466	436	6.5	45	Low
15A	532	502	512	477	6	15	High
5C	477	457	458	427	5.5	15	Low
11D	485	456	467	437	6.5	45	Low
13A	537	441	514	466	6	15	High
7D	484	448	473	437	4.5	15	Low
6D	504	455	469	403	11.25	15	Low
1C	486	477	469	441	5.25	15	Low
7A	520	484	505	443	5	15	High
1A	525	508	501	474	5.5	15	High
7B	525	470	527	487	5	45	High
7C	487	478	463	435	5.23	45	Low
13D	515	455	502	455	9.5	45	High
1B	481	457	459	435	5	45	Low
13B	495	455	483	440	5	45	Low
4B	555	464	532	443	13	45	High
11A	482	449	462	432	8	15	Low
11B	533	477	521	476	6.5	15	High
13C	479	444	469	434	6.5	15	Low
6A	492	425	514	432	14	15	High
6B	495	432	476	402	15.83	45	Low
6C	499	433	535	441	9.25	45	High
11C	523	474	526	473	6	45	High
4C	508	449	494	412	12	15	Low
16B	498	425	526	420	12.2	15	High
4A	546	465	522	433	12	15	High
4D	490	432	482	403	13	45	Low
16A	459	401	392	482	11.5	45	Low
10C	526	447	506	413	17.5	45	High
16C	552	439	517	417	20	45	High
16D	449	407	480	388	13	15	Low
10D	535	433	522	423	15	45	High
10B	529	451	549	430	N/A	15	High
10A	484	410	480	391	N/A	15	Low

Appendix C. Flexure Test Data

Panel #	Ultimate Strength (psi)	Failure Mode
C1	130,688	
	132,352	
	132,038	
	133,036	
	131,254	
	133,524	
C2	113,203	Tension/Compression
	107,421	"
	107,915	Tension
	112,575	"
	107,201	Tension/Compression
	106,517	"
Note: Failures are mostly tensile.		
C3	130,464	Tension
	121,586	Compression/Tension
	116,820	"
	124,133	Tension
	116,625	"
	119,517	Compression/Tension
C4	146,046	Tension/Compression
	144,368	"
	141,251	"
	133,560	"
	141,949	"
	136,875	"
C5	116,237	
	121,847	
	122,399	
	112,783	
	120,013	
	119,206	
C6	80,697	Tension/Compression
	86,524	Compression
	89,110	"
	84,963	Tension/Compression
	80,808	Tension
	79,392	Tension/Compression

Panel #	Ultimate Strength (psi)	Failure Mode
C7	156,803	
	154,542	
	154,691	
	155,729	
	154,608	
C8	118,855	Tension
	118,286	Tension/Compression
	116,977	Tension/Compression
	120,604	Tension
	120,310	Compression/Tension
	113,220	Tension/Compression
C9	123,828	
	123,962	
	128,771	
	120,552	
	121,097	
	125,594	
C10	101,168	Tension/Compression
	97,294	
	106,913	
	104,240	
	107,541	
	108,010	
C11	165,121	
	174,002	
	174,542	
	178,777	
	176,587	
C12	140,942	
	138,605	
	137,344	
	146,362	
	140,291	
	138,110	
8C	110,791	Compression
	119,658	"
	108,799	Compression/Tension
	109,918	Compression
	126,322	Tension

Panel #	Ultimate Strength (psi)	Failure Mode
C13	108,022	Tension/Compression
	110,127	
	105,847	
	107,541	
	107,233	
	114,350	
Note: Compression first but load continues until ultimate failure.		
C15	134,161	
	144,025	
	146,437	
	145,681	
	138,993	
	136,576	
C16	135,097	Tension/Compression
	131,829	
	137,814	
	126,861	
	130,239	
	129,751	
Note: Compression first but load continues until ultimate failure.		
2B	95,839	Compression/Tension
	108,293	"
	105,191	"
	93,867	"
	97,868	"
$3C_2$	162,939	Compression/Tension
	159,626	"
	155,511	"
	163,669	"
	160,605	"
	169,324	"
5B	109,052	Compression/Delamination
	103,479	
	120,323	
	112,763	
	110,060	
	107,303	

Panel #	Ultimate Strength (psi)	Failure Mode
9D	123,126	Compression/Tension
	122,472	"
	119,810	"
	121,257	"
	122,849	"
	124,876	"
12A	134,781	Compression/Tension
	144,090	"
	145,442	"
	149,320	"
	147,157	"
14C	44,820	Compression
	43,225	Compression/Tension
	46,556	Compression
	47,598	Compression
	54,192	Compression/Tension
15C	34,858	Delamination
	50,522	Delamination/Compression
	91,371	Delamination/Compression
	24,058	Delamination
	80,129	Delamination
	76,142	Compression/Delamination
2D	85,727	Tension
	79,335	"
	81,537	"
	76,685	"
	80,299	"
3A	185,549	Tension
	178,685	"
	178,632	"
	182,163	"
	193,668	"
	183,117	"
8A	60,930	Delamination
	65,011	Delamination/Tension
	68,367	Delamination
	64,495	Delamination
	71,220	Delamination/Tension

Panel #	Ultimate Strength (psi)	Failure Mode	Panel #	Ultimate Strength (psi)	Failure Mode
5A	96,707	Tension/Compression	12D	138,561	Compression/Tension
	96,862	"		134,669	"
	92,693	"		137,670	"
	35,803	Delamination		143,268	"
	40,000	Tension/Compression		136,542	"
	81,164	"			
			15B	135,942	Tension
9A	118,624	Compression		128,381	"
	129,505			144,827	"
	124,863			141,597	"
	128,211	Compression		152,734	"
	130,228	Compression		138,368	"
	119,689				
			2A	96,667	Compression
14A	72,477	Tension		91,864	Compression/Tension
	75,058	Compression/Tension		97,059	"
	73,375	"		97,003	"
	71,901	"		95,248	"
	81,275	Tension			
			5D	44,257	Shear/Delamination
3B	161,735	Shear/Tension		87,292	Compression/Tension
	163,228	Compression/Tension		104,727	Tension
	165,380	"		52,332	Shear/Delamination
	175,731	Compression/Shear		94,409	Compression/Tension
	159,060	Comp/Tension/Shear		90,484	Compression/Tension
	166,619	Compression/Tension	Spec. #1,4 and 5 had delaminations before testing.		
8B	114,140	Compression/Tension	12B	78,931	Delam./Tension/Compression
	112,156	Compression		79,556	Delam./Compression/Tension
	108,500	Compression/Tension		93,090	"
	110,137	Compression/Tension		102,025	"
	99,873	Compression/Tension		75,942	"
9C	68,951	Shear/Delamination	14B	84,012	Compression/Tension
	77,871	Shear/Delamination		80,729	"
	114,423	Compression/Shear		78,585	"
	75,149	Shear/Tension		82,366	Tension
	87,510	Shear		81,119	"
	105,718	Compression/Shear			
Spec. #1,2,4 and 5 had delaminations before testing.			14D	80,885	Compression/Tension
				80,892	"
15D	122,674	Tension		80,021	"
	138,467	Tension		80,694	"
	139,907	Compression/Tension		83,786	"
	135,771	Compression/Tension			
	135,266	Tension			
	135,836	Tension			

Panel #	Ultimate Strength (psi)	Failure Mode
1D	73,690	Shear/Tension
	56,014	"
	44,790	Shear
	30,364	"
	26,489	"
	28,281	"
2C	27,798	Compression/Shear
	28,190	"
	26,700	"
	29,144	"
	37,180	Compression/Temsion
3D	70,419	Shear
	70,040	
	73,966	Shear
	83,641	Shear
	122,742	Shear/Tension
	67,758	Shear
All specimens had delaminations before testing.		
5C	108,845	Tension
	122,315	"
	123,714	"
	121,600	"
	119,492	"
	123,481	"
8D	124,160	Tension
	125,953	Shear
	122,457	Tension
	127,904	"
	128,978	"
9B	138,951	Compression
	128,460	"
	134,262	"
	140,299	"
	137,318	"
	137,587	"
12C	139,092	Compression/Shear-Tension
	134,235	Shear/Tension
	140,800	Compression/Shear
	143,104	Compression/Shear-Tension
	139,378	"

Panel #	Ultimate Strength (psi)	Failure Mode
4B	72,700	Tension
	64,690	"
	60,190	"
	76,060	"
	79,480	"
6D	72,987	Compression/Tension
	67,884	"
	73,867	"
	69,901	"
	69,010	"
All specimens had delaminations before testing.		
7D	102,052	Shear
	63,162	"
	62,017	"
	97,049	"
	105,989	"
	128,464	"
All specimens had delaminations before testing.		
10C	52,917	
	34,782	
	32,240	
	38,190	
	30,511	
11D	165,337	Compression/Tension
	162,222	Compression
	164,403	Compression/Tension
	155,901	Compression/Shear
	159,094	"
	168,691	"
13C	30,020	Tension
	33,310	"
	67,980	"
	25,850	"
	27,670	"
	64,340	"
16D	114,172	
	117,743	
	114,932	
	122,784	
	117,972	

Panel #	Ultimate Strength (psi)	Failure Mode
13A	15,530	Shear
	31,967	"
	13,890	"
	18,240	"
	15,735	"
	18,018	"
16B	33,786	Shear/Compression
	49,989	Compression
	64,022	"
	70,503	Compression/Shear
	65,129	Compression
1B	154,485	Shear
	151,093	"
	170,100	"
	153,360	"
	149,505	"
	143,968	"
4D	112,655	Shear/Tension
	147,115	Compression/Tension
	139,428	"
	131,764	"
	133,639	"
6A	77,630	Compression/Tension
	59,840	"
	59,930	"
	56,810	"
	60,890	"
7A	26,991	Shear
	53,182	Tension
	48,973	Shear
	35,888	"
	57,379	"
	75,060	Compression/Tension
10D	34,694	
	29,597	
	25,904	
	29,206	
	24,510	

Panel #	Ultimate Strength (psi)	Failure Mode
1C	135,410	Compression/Tension
	139,456	"
	127,108	"
	136,944	"
	135,056	"
	137,407	"
4C	90,472	Shear/Compression/Tension
	83,490	Compression/Tension
	79,693	Shear/Tension
	92,958	Tension
	94,178	Shear/Tension
1A	91,616	Shear
	78,142	"
	70,323	"
	122,707	"
	139,666	"
	121,856	"
Specimens #2 and 3 had delaminations before testing		
4A	100,880	Compression/Tension
	105,526	"
	109,608	"
	112,076	"
	119,734	"
6B	65,860	Tension/Compression
	59,130	"
	59,610	"
	54,130	"
	59,640	Compression
6C	40,840	Compression/Tension
	35,030	Tension
	36,790	"
	53,690	"
	55,670	
All Specimens delaminated before testing		
11C	34,250	Delamination
	34,060	"
	35,400	"
	50,820	"
	51,200	"
	44,520	"

Panel #	Ultimate Strength (psi)	Failure Mode
7C	139,396	Tension
	146,908	"
	141,690	"
	144,724	"
	134,558	"
	141,067	"
10A	116,909	
	106,811	
	106,648	
	106,072	
	105,253	
11A	206,560	Compression/Tension
	186,270	"
	195,590	"
	205,600	"
	192,150	"
	213,850	"
13D	12,397	Shear
	10,981	"
	15,050	"
	24,525	"
	19,473	"
	9,383	"

All specimens had delaminations before testing.

Panel #	Ultimate Strength (psi)	Failure Mode
16C	17,465	
	24,545	
	18,224	
	15,903	
	19,603	
1C	135,410	Compression/Tension
	139,456	"
	127,108	"
	136,944	"
	135,056	"
	137,407	"
15A	153,362	Tension
	147,429	"
	142,881	"
	151,865	"
	156,785	"
	149,358	"

Panel #	Ultimate Strength (psi)	Failure Mode
7B	12,379	Shear
	13,147	"
	11,381	"
	19,120	"
	34,805	"
	55,196	"

All Specimens delaminated before testing

Panel #	Ultimate Strength (psi)	Failure Mode
10B	76,324	
	67,960	
	78,035	
	63,704	
	70,939	
11B	91,570	Tension
	76,070	"
	81,350	Delamination
	58,640	"
	83,790	Tension
	82,180	"
13B	44,077	Tension
	50,689	Shear
	52,466	Tension
	49,240	Shear
	60,094	Shear/Tension
	47,989	"
16A	40,451	Compression
	71,016	Compression/Tension
	52,029	"
	42,720	Compression
	34,913	"
4C	90,472	Shear/Compression/Tension
	83,490	Compression/Tension
	79,693	Shear/Tension
	92,958	Tension
	94,178	Shear/Tension
C14	86,823	Tension/Compression
	91,475	"
	87,691	"
	82,822	"
	86,270	"
	84,702	"

Appendix D. Shear Test Data

Panel #	Ultimate Strength (psi)	Failure Mode	Panel #	Ultimate Strength (psi)	Failure Mode
C1	9,357		C7	7,839	
	9,658			8,023	
	8,708			8,384	
	9,176			8,466	
	8,809			8,406	
	8,644			8,150	
C2	7,079		C8	7,515	
	7,724			6,898	
	7,847			7,686	
	7,130			7,121	
	7,125			7,266	
	7,292			7,296	
C3	10,879	Shear	C9	8,426	
	10,364	"		8,119	
	9,772	"		7,897	
	9,844	"		7,694	
	10,668	"		7,358	
	10,193	"		8,351	
C4	8,198		C10	6,650	Tension/Compression
	8,413			7,071	
	8,315			7,107	
	8,109			7,628	
	8,250			7,612	
	8,824			7,469	
C5	7,533		C11	10,876	
	7,485			10,585	
	8,059			11,247	
	7,841			11,226	
	8,001			10,603	
	7,886			10,488	
C6	5,239		C12	8,517	
	5,243			8,306	
	5,405			8,383	
	5,209			7,918	
	5,270			8,502	
	5,899			8,107	
			8C	6,463	Compression then Shear
				7,099	"
				7,084	"
				6,792	"
				6,460	"

Panel #	Ultimate Strength (psi)	Failure Mode	Panel #	Ultimate Strength (psi)	Failure Mode
C13	7,603	Tension/Compression	9D	8,610	Shear
	7,659			8,303	"
	7,141			7,910	"
	7,648			8,850	Shear/Tension
	7,392			7,783	Shear
	6,903			8,758	Compression/Shear
C14	5,559		12A	7,825	Compression then Shear & Tension
	5,425			8,066	"
	5,857			9,181	"
	5,579			8,645	"
	5,539			8,937	"
	5,628				
			14C	3,254	Compression/Tension
C15	8,443			3,397	Compression
	9,156			3,251	Compression/Tension
	8,655			2,939	Compression/Tension
	9,412			3,259	Compression/Tension & Shear
	9,051		All Specimens with Delamination before Testing		
	8,538				
			15C	2,010	
C16	8,214			2,656	
	7,958			5,281	
	8,381			2,399	
	8,227			5,658	Compression/Delamination
	8,213			6,316	Compression/Delamination
	8,029		Specimens 1,2,4 and 5 have Delamination before Testing		
2B	6,426	Compression/Tension then Shear	2D	5,222	Tension
	6,177	"		5,237	"
	5,955	"		5,392	"
	6,538	"		5,287	"
	6,541	"		5,016	"
$3C_2$	6,588	Delamination/Shear	3A	9,289	Shear
	8,308	"		8,032	"
	7,468	"		7,517	"
	6,280	"		10,064	"
	7,492	"		10,476	"
	6,247	"		9,651	"
5B	6,616	Compression/Delamination	8A	4,283	Shear
	6,213			4,706	Shear/Tension
	5,183			4,162	"
	5,549			4,775	"
	5,368			4,866	Shear
	5,657		All Specimens had Delaminations before Testing		

Panel #	Ultimate Strength (psi)	Failure Mode
5A	4,056	
	4,848	
	5,056	
	2,834	
	3,114	
	4,677	
Specimens 4,5 and 6 had Delamintions before Testing		
9A	5,179	Shear
	6,103	"
	6,098	"
	5,764	"
	5,898	"
	5,856	"
14A	4,022	Tension
	4,657	"
	4,522	"
	4,707	"
	4,699	"
Specimens 1,2 and 3 had Delaminations before Testing.		
3B	5,894	Shear
	6,513	"
	6,439	"
	6,613	"
	6,256	"
	6,132	"
8B	6,899	Compression/Shear
	6,869	Shear
	7,179	Compression/Shear
	7,000	Compression/Tension
	6,428	Compression/Tension
9C	3,511	Shear
	3,683	"
	4,527	"
	3,492	"
	4,497	"
	4,580	"
Spec. #1,2, and 4 had delaminations before testing.		
15D	9,014	Shear
	7,559	Shear/Tension
	8,646	Tension
	8,064	Shear
	8,534	Tension
	7,778	Shear

Panel #	Ultimate Strength (psi)	Failure Mode
12D	8,440	Shear
	8,862	Shear/Tension
	8,894	Shear
	8,976	"
	8,433	Shear/Tension
15B	7,113	
	6,413	
	7,285	
	6,931	
	7,062	
	7,259	
2A	6,967	Shear
	7,268	"
	7,579	Compression/Shear
	7,652	Shear
	6,529	"
5D	1,789	Compression/Shear
	4,364	Shear
	6,306	"
	3,722	Compression/Shear
	4,499	Shear
	6,861	"
Spec. #1,2,4 and 5 had delaminations before testing.		
12B	5,016	Delam./Tension/Compression
	5,085	Delam./Compression/Tension
	6,145	"
	5,485	"
	6,302	"
Spec. #1,2, and 5 had delaminations before testing.		
14B	4,703	Compression/Tension
	4,923	"
	5,067	Tension
	5,219	Compression/Tension
	5,432	"
14D	5,238	Compression/Tension
	5,206	"
	4,895	Tension
	5,174	Compression/Tension
	5,265	"

Panel #	Ultimate Strength (psi)	Failure Mode
1D	3,169	Shear
	2,454	"
	2,145	"
	1,471	"
	1,136	"
	1,865	"

All Specimens had Delaminations Before Testing.

Panel #	Ultimate Strength (psi)	Failure Mode
2C	2,346	Compression/Shear/Tension
	2,191	"
	2,278	Compression/Shear
	2,441	"
	2,932	"

All Specimens had Delaminations before Testing

Panel #	Ultimate Strength (psi)	Failure Mode
3D	3,177	Shear
	3,492	"
	3,253	"
	2,567	"
	2,631	"
	3,148	"

All specimens had delaminations before testing.

Panel #	Ultimate Strength (psi)	Failure Mode
5C	7,409	Shear
	6,578	"
	7,131	"
	6,680	"
	7,078	"
	6,331	"
8D	7,546	Shear
	7,647	"
	8,050	"
	7,579	Shear/Tension
	8,128	Shear
9B	6,495	Shear
	6,246	"
	6,724	"
	6,045	"
	7,408	"
	6,336	"
12C	8,344	Shear
	8,092	"
	8,044	"
	8,076	"
	8,169	"

Panel #	Ultimate Strength (psi)	Failure Mode
15A	7840	Shear
	6937	"
	7686	"
	6652	"
	7084	"
	7273	"
4B	4,050	Compression/Tension(Delamination)
	2,150	Compression(Delamination)
	3,760	Compression/Tension(Delamination)
	4,140	Compression/Tension(Delamination)
	4,270	Compression/Tension(Delamination)
6D	4,714	Compression/Tension
	4,525	"
	4,626	"
	4,661	"
	4,440	"

All specimens had delaminations before testing.

Panel #	Ultimate Strength (psi)	Failure Mode
7D	1,818	Shear
	1,810	"
	2,762	"
	1,533	"
	1,116	"
	1,685	"

All specimens had delaminations before testing.

Panel #	Ultimate Strength (psi)	Failure Mode
10C	3,554	
	3,246	
	1,679	
	1,607	
	1,370	
11D	6,351	Shear
	7,129	"
	7,047	"
	4,936	"
	7,452	"
	6,240	"
13C	3,960	Shear
	3,880	"
	2,700	"
	1,590	"
	3,670	"

Panel #	Ultimate Strength (psi)	Failure Mode
13A	1,161	Shear
	1,550	"
	892	"
	597	"
	669	"
	1,305	"

All specimens had delaminations before testing.

Panel #	Ultimate Strength (psi)	Failure Mode
16B	4,392	Compression/Shear
	3,169	Shear/Compression
	2,321	"
	4,693	"
	4,123	"
1B	4,376	Shear
	6,334	"
	4,682	"
	4,750	"
	4,788	"
	5,221	"
4D	7,338	Shear/Tension
	7,305	Shear
	7,474	"
	7,447	"
	7,802	"
6A	5,260	Compression/Tension
	3,980	"
	3,850	"
	3,530	"
	4,530	"
7A	3,770	Shear
	5,277	"
	5,641	"
	2,342	"
	3,614	"
	4,004	Shear/Tension
10D	2,996	
	2,249	
	1,902	
	1,251	
	1,442	

Panel #	Ultimate Strength (psi)	Failure Mode
16D	6,496	
	6,995	
	6,681	
	6,672	
	6,694	
1C	5,797	Shear
	6,465	"
	6,413	"
	5,338	"
	6,283	"
	5,467	"
4C	6,075	Tension/Compression
	5,675	Tension/Compression/Shear
	5,843	Tension/Shear
	6,340	Tension/Compression/Shear
	6,373	Shear
1A	4,269	Shear
	4,321	"
	3,506	"
	4,214	"
	4,283	"
	4,404	"

Specimens #3 had delaminations before testing

Panel #	Ultimate Strength (psi)	Failure Mode
4A	6,963	Shear/Compression
	6,578	"
	7,148	"
	6,906	Shear/Compression/Tension
	6,603	"
6B	3,770	Compression/Tension
	3,880	"
	3,740	"
	3,750	"
	3,810	"
6C	2,500	
	2,550	
	2,620	
	3,290	
	3,540	

All Specimens delaminated before testing

Panel #	Ultimate Strength (psi)	Failure Mode
7C	5,055	Shear
	5,594	"
	5,573	"
	5,434	"
	5,288	"
	4,960	"
10A	6,917	
	6,944	
	6,592	
	7,020	
	6,852	
11A	6,360	Shear
	7,820	"
	6,960	"
	7,530	"
	7,140	"
	8,090	"
13D	909	Shear
	491	"
	890	"
	1,025	"
	947	"
	755	"
16C	1,111	
	803	
	1,213	
	1,032	
	1,373	
11C	3,480	Delamination
	3,790	"
	3,380	"
	4,300	"
	3,570	"
	4,600	"
7B	416	Shear
	398	"
	592	"
	1,711	"
	2,597	"
	3,434	"
All Specimens delaminated before testing		
10B	4,591	
	4,962	
	4,317	
	4,142	
	4,174	
11B	4,830	Shear
	3,690	"
	3,870	"
	4,980	"
	4,660	"
	4,730	"
13B	2,980	Shear/Tension
	2,879	"
	2,972	"
	1,799	Shear
	2,747	"
	2,877	"
16A	2,476	Compression/Shear
	3,661	Shear
	3,826	Compression
	3,569	Shear
	3,487	"